University of Alberta

An Integrated Framework for Evaluation, Forecasting and Optimization of Performance of Construction Projects

by

Nadim Kamil Nassar ©

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Dedicated to my Wife Aline
. . . . for Her Constant
Understanding and Support
During the Many Hours Required
to Accomplish this Work

ABSTRACT

Performance management of construction projects is one of the most challenging and critical tasks carried out by construction organizations. The successful delivery of construction projects requires management of all project aspects. The main objective of this research is to develop an integrated framework for evaluation, forecasting and optimization of performance of construction projects. This research focuses on the construction phase of a project and is intended for implementation by contractors.

This research presents a systematic and comprehensive integrated model for performance management. A systematic and unified construction performance measurement methodology was developed to evaluate and integrate all project objectives including cost, schedule, cashflow, profitability, safety, quality, project team satisfaction, and client satisfaction. Using dynamic Markov Chains, a stochastic model was developed to forecast the dynamic nature of construction performance. The forecasting model incorporates user feedback, historic trends, and latest project status to predict the performance of any objective at any future time and at project completion. Moreover, the integrated model offers an innovative mechanism, using genetic algorithms, to assist users select corrective action plans that lead to better project performance. In addition, this research proposes the concept of a guide in a matrix form to resolve contradictions among the various performance indices. This research introduced a framework for managing a distributed project performance system using multi agent systems. It also

included an extensive literature review that identified and discussed specific work related to measurement, forecasting, and optimization of performance of construction projects.

The proposed integrated framework is unique in the sense that it is mathematically derived and it deals with a single project phase. Although the proposed methodology is intended for use by contracting companies during the construction phase, it can be adapted for use by any project-driven company during any phase of a project.

The proposed system is based on quantitative models, but it does not eliminate the role of sound subjective judgment and feedback by users. It offers a tool to assist construction managers better plan their projects through efficient and effective decision-making.

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List of Nomenclature and Abbreviations

ACL	agent communications language
ACV	At-completion Cost Variation
ACWP	Actual Cost of Work Performed
ACWP_L	Actual Labour Cost of Work Performed
AFD	Anticipatory Failure Determination
AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
APP	Actual Project Performance
APPM	Agent-based Project Performance Management
ARIZ	Algorithm for Inventive Problem Solving
ATV	At-completion Time Variation
AV	Actual Value
BAC	Budget At Completion
$BC(t)$	Total Current Budgeted Cost as of time period "*t*"
BCWP	Budgeted Cost of Work Performed
BCWP_L	Budgeted Labour Cost of Work Performed
$BCWP(t)$	Total Budgeted Cost of Work Performed as of time period "*t*"
BCWS	Budgeted Cost of Work Scheduled
BPI	Billing Performance Index
BPI_B	Building Works Billing Performance Index
BPI_F	Off-site Fabrication Billing Performance Index
BPI_S	Site Works Billing Performance Index
BPI_t	Forecasted Billing Performance Index at time *t*
BRWP	Billed Revenue of Work Performed
c_i	Self-contribution part to the absolute weight of Index I_i
C(n,1)	possible combinations of "*n*" activities where each activity has a single activation period
$C(n,N_i)$	possible combinations of *n* activities with each activity *i* having N_i activation periods
C_t	Condition, or Project Performance at time t
C_{t+1}	Condition, or Project Performance at time t+1
$C_v(t)$	Total Project Cost Variance as of time period "*t*"
CFRI	Construction Field Rework Index
CGS	Cost Growth
CI	Consistency Index
COAA	Construction Owners Association of Alberta
CPI	Cost Performance Index
CPI_A	Average CPI value for *outstanding* performance
CPI_B	Average CPI value for *above target* performance
CPI_C	Average CPI value for *within target* performance
CPI_C	Construction Equipment Cost Performance Index
CPI_D	Average CPI value for *below target* performance

CPI_E	Engineering Cost Performance Index
CPI_F	Average CPI value for *poor* performance
CPI_I	Indirect Cost Performance Index
CPI_L	Labor Cost Performance Index
CPI_M	Material Cost Performance Index
CPI_S	Subcontractor Cost Performance Index
CPI_t	Forecasted Cost Performance Index at time t
CPI_T	Tools/consumables Cost Performance Index
CPI_{3mo}	3-Months Average Cost Performance Index
CPM	Critical Path Method
CR	Consistency Ratio
CSI	Client Satisfaction Index
CSI_t	Forecasted Client Satisfaction Performance Index at time t
CV	Cost Variance to-date
CWP	Construction Work Package
DAC	Duration At Completion
DAI	Distributed Artificial Intelligence
DPE	Directed Product Evolution
EAC	Estimate At Completion
$EAC(t)$	Total Estimate at Completion Cost as of time period “t”
ERP	Enterprise Resource Planning
ERWP	Earned Revenue of Work Performed
ETWP	Elapsed Time for Work Performed
EV	Earned Value
EVMS	Earned-Value Management System
f_c	constraint fitness for string j
f_i	performance of constraint i
f_j	fitness value of string j
$f^{n)}{}_{ij}$	first passage probability
f_o	objective performance fitness for string j
F_i	forecasted value for constraint I
FCPI	Forecasted Cost Performance Index for the remaining work
G	Goal
G_A	*Change in Urge Intensity of Agent A*
GAs	Genetic Algorithms
GP	Gap Performance
I_A	Urge Intensity of Agent A
I_C	Critical or threshold value of index (I)
I_i	Performance Index i
$I_i(t)$	Performance index i at time t
I_T	performance index value at time “T”
IFR	Ideal Final Result
IPPM	Integrated Project Performance Evaluation Model

LOI	Level Of Impact
LTI	Lost Time Incident
M	Total man hours expended to date
M	maximum project performance index
M_v	Magnitude of adjustment to the transition probability curves in %
MAS	Multi-Agent Systems
MSAT	Multiple Simulation Analysis Technique
MSFE	Mean Square Forecasting Errors
n	Size of Matrix
NCR	Non-Conformance Report
P	Process
P_{ij}	Transition probability of a system changing from state i at time t to state j at time $t+1$
p_j	selection probability of string or plan j
PCM	Performance Contradiction Matrix
PDF	Probability Distribution Function
PDWP	Planned Duration for Work Performed
PERA	Number of activities actually completed as of the report data date
PERAC	Number of activities completed as planned at completion
PERBL	Number of activities planned to be completed as of the report data date
PERT	Program Evaluation and Review Technique
PI	Project Performance Index
$PI(t)$	project performance index at time t
PPFM	Project Performance Forecasting Model
PPI	Profitability Performance Index
PPI_C	Profitability Performance Index for Concrete Works
PPI_E	Profitability Performance Index for Electrical Works
PPI_M	Profitability Performance Index for Mechanical Works
PPI_t	Forecasted Profitability Performance Index at time t
PPI_V	Profitability Performance Index for Civil Works
PPOM	Project Performance Optimization Model
PRPC	Principles for Resolving Performance Contradictions
QPI	Quality Performance Index
QPI_t	Forecasted Quality Performance Index at time t
r_i	Measure of Dependency of Index I_i
R	Resource
R_i	Satisfaction Rating
RC	Random Consistency Index
s_i	Self-contribution % of w_i
S	Sub-goal
S_A	Amount of satisfaction received by Agent A
SFI	Safety Performance Index
SFI_t	Forecasted Safety Performance Index at time t
SGS	Schedule Growth

SJT	Social Judgment Theory
SPI	Schedule Performance Index
SPI_t	Forecasted Schedule Performance Index at time *t*
STWP	Scheduled Time of Work Performed
SV	Schedule Variance
T	planned project duration
T_a	actual elapsed duration
T_e	time duration corresponding to the percentage of earned progress
T_f	forecasted project completion time
T_i	threshold value for constraint *i*
T_{ij}	first passage time
T_s	scheduled project completion time
T_{SC}	expected first passage time
T_V	goal threshold value
TAC	Time At Completion
TBL	Baseline completion date
TPC	Transition Probability Curve
TPI	Time Performance Index
TPP	Target Project Performance
TRAC	Techniques for Resolving Performance Contradictions
TRIZ	Theory of Inventive Problem Solving
TSI	Team Satisfaction Index
TSI_t	Forecasted Team Satisfaction Performance Index at time *t*
TV	Time Variation to-date
TV_{ac}	Time Variance at completion
TV_{dd}	Time Variance to-date
U	global goal
V	Inertia Vector
V_B	Billing Variance
V_C	Cost Variance
V_i	violation of constraint *I*
V_S	Schedule Variance
V_T	Time Variance
VE	Value Engineering
w	Eigen Vector
w_i	Weight of performance index I_i
$w_{CPI}(t)$	Priority weight of Cost Performance Index at time *t*
$w_{SPI}(t)$	Priority weight of Schedule Performance Index at time *t*
$w_{BPI}(t)$	Priority weight of Billing Performance Index at time *t*
$w_{PPI}(t)$	Priority weight of Profitability Performance Index at time *t*
$w_{SFI}(t)$	Priority weight of Safety Performance Index at time *t*
$w_{QPI}(t)$	Priority weight of Quality Performance Index at time *t*
$w_{TSI}(t)$	Priority weight of Team Satisfaction Index at time *t*

$w_{CSI}(t)$	Priority weight of Client Satisfaction Index at time *t*
W	Pair-wise comparison matrix
WBS	Work Breakdown Structure
λ_{max}	Maximum Eigen Value

Chapter 1

Introduction

1.1 General

The construction industry is characterized as mature because of the overall reduction in profitability and increased competition. In addition, the construction industry has frequently been described as being dynamic. At the project level, project managers are continuously confronted with performance problems and uncertainties in the construction workplace. To gain a competitive edge in an extremely competitive and continuously changing construction environment, construction managers need to make timely and informed decisions that will enable them to manage the project's various performance attributes effectively.

It is widely recognized that deficiencies in monitoring and control of construction operations is one of the major causes for project failures. North American construction companies are currently operating in very competitive environments. To ensure profit and growth, contractors must evaluate and improve the performance of projects, not only with regard to schedule and cost, but also safety, quality, project team, and client satisfaction. Facing reduced profit margins and a competitive market, senior management of construction organizations now realize the importance of project performance evaluation and management. However, they lack the right and effective decision-support tools. The lack of prompt management action will increase the risk to the project. The existing systems do not integrate the various phases of performance, which is evaluation, forecasting, and implementing corrective action. This research aims at filling this gap by offering an integrated project performance management system for use by the construction industry. If implemented, the proposed research can provide construction organizations with an effective project controls tool to better manage their construction operations.

Under the current level of competition, projects are being implemented in complex, dynamic, and uncertain environments. As project management is getting more integrated, performance measurement of projects is expanding to include more parameters than the two traditional cost and schedule. Today, traditional project performance management models are not sufficient for managing all project aspects and do not present a comprehensive project success model. The perception of failure and success of projects is usually based on subjective evaluations. Also, linear trending and index-based current forecasting techniques cannot model the dynamic and stochastic nature of performance.

As a result, contractors being project-oriented organizations need to use a unified performance measurement system that integrates and evaluates all project attributes. Moreover, the lack of effective forecasting tools, distributed project control, and project performance conflict resolution techniques hinder construction planners from taking timely corrective action to improve performance.

1.2 Background

The project control process generally consists of two phases: measurement, and decision-making. The process is composed of seven major activities as shown in Figure 1.1. These activities are: (1) development and approval of baselines, (2) data collection, (3) evaluation of project performance, (4) performance forecasting, (5) reasoning and variance analysis, (6) generation of viable corrective action activities, and (7) selection and implementation of corrective action plans to improve project performance.

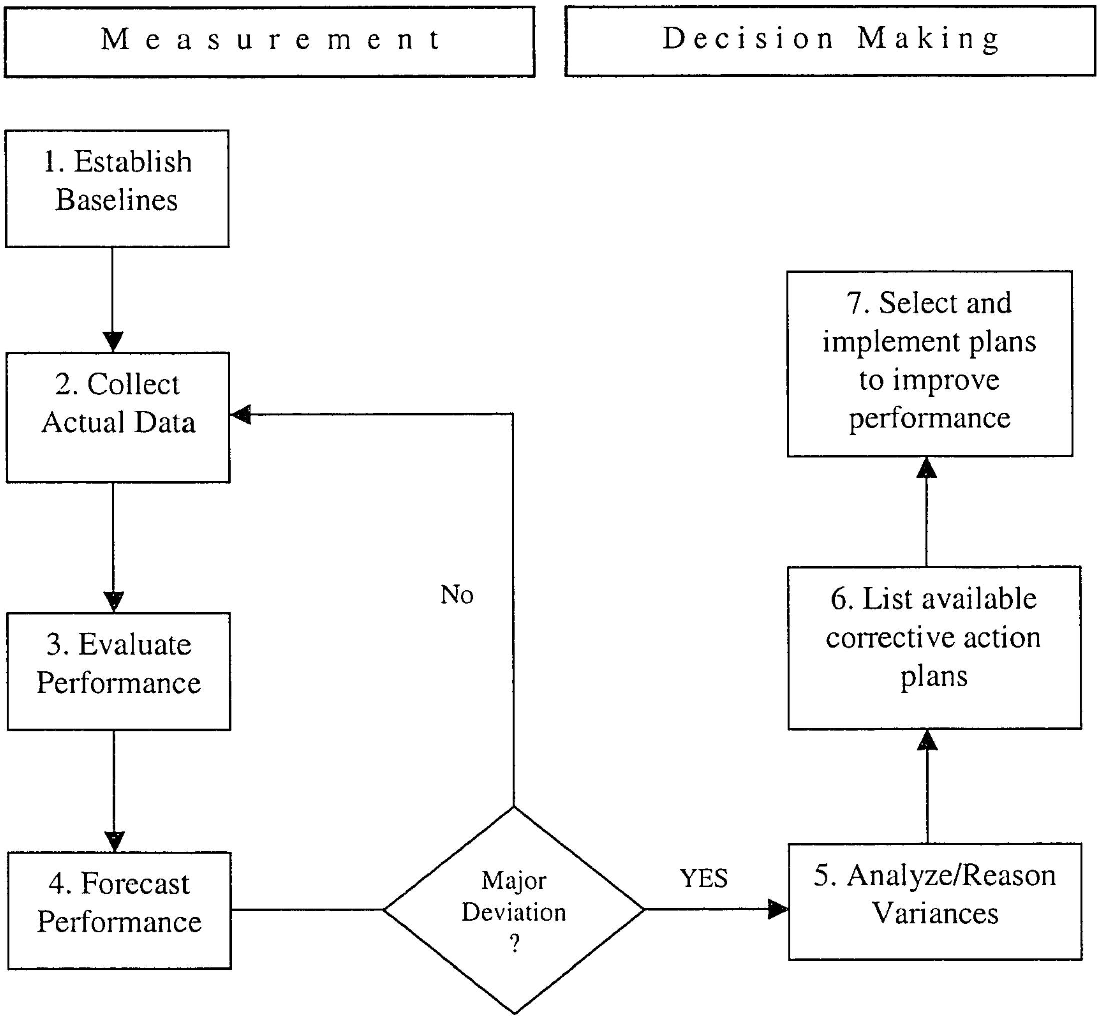


Figure 1.1 The Project Control Process

Project baselines serve as a reference or benchmark in a project controls system. An approved construction schedule is a time baseline and an approved budget is a cost baseline. There can be other baselines that a construction company can set for a project like safety, quality, and profitability baselines. Baselines or planned S-Curves are needed to carry out variance analysis and to measure the earned value. Baselines can only be established in case of a defined statement of scope and a Work Breakdown Structure (WBS). A WBS breaks a large project into smaller manageable operative units (Nassar et al. 2003 and Moselhi 1991).

Traditionally, the techniques used to measure performance lacked the integration of cost and schedule (Douglas 1993). The earned value method, introduced by the US Department of Defense (DoD) in 1967, can calculate the schedule and cost variance in an integrated manner (Christensen 1994). This method is widely applied within the construction industry to measure the performance of projects. It can also identify any cost and schedule variances at the end of the project but cannot identify the corrective action plans that need to be taken to minimize any negative variances. Each of the critical variances identified usually requires a formal analysis to determine the cause of the variance, the corrective action to be taken, and the effect on the forecasted project performance at completion.

Forecasting is the exercise of predicting the project performance at completion based on current performance. Forecasting is one of the most important project management tools that help decision makers to propose and implement the right corrective action plans. Many forecasting methods, including the earned value method, have been proposed in the literature and will be later reviewed in Chapter 3. Most of these methods use trending and index-based formulae as a basis of forecasting.

Figuring out the reasons behind variances, especially the negative ones, is a critical process within the project controls cycle. It is a pre-requisite for proposing relevant and effective corrective actions. In current practice, this exercise is mainly achieved using the project manager's own experience or some rules of thumb that some construction contractors developed over time. Within academia, some efforts have been made to assist project managers identify the reasons behind negative variances using a knowledge-based approach (Diekmann and Altabtabai 1992) and/or fuzzy reasoning methodology (Russell and Fayek 1994).

1.3 Significance of Project Controls within the Construction Industry

The successful delivery of construction projects requires progress monitoring and control (Moselhi 1991). Monitoring is the process of tracking and highlighting variations from established baselines during the project execution phase. Monitoring also involves diagnosis and highlight of the reasons leading to negative slippages. Control refers to the corrective action decision-making process to minimize the unfavorable variations. As such, a project controls system should be able to evaluate progress, forecast and highlight variations, in an integrated, analytical, and systematic manner. In addition, such a system should be able to assist decision makers to identify possible corrective action. Moreover, an effective controls system must inter-relate all the project functions and must provide managers with information needed for forecasting and responsive control.

The Canadian construction industry plays a significant role in Canada's economy. In Alberta, the construction industry is a major sector of the economy and many mega projects that are underway are experiencing major cost, and schedule overruns. Moreover, many projects are expected in the near future especially in the oil/gas and pipelines sectors. As a result, a well-defined integrated system is highly needed.

An adequate tracking and control system can minimize slippages and assist project management is delivering successful projects. Moreover, it can maximize profit and put the implementing company at a competitive edge. In practice, most construction companies employ some methods for schedule/cost control. However, these methods suffer from the lack of integration between evaluation, forecasting, and optimization of performance.

This research presents an integrated model for measuring, forecasting and improving project performance of construction projects. The proposed system presents a unified and structured approach for measurement of success of construction projects. The proposed model is unique in the sense that it is quantitatively derived, and it deals with a single project phase (Construction). As per the Construction Industry Institute - CII (1995), the construction phase starts with beginning of continuous substantial construction activity and ends with *mechanical completion.* In this research it is proposed that the project performance during the construction phase is expressed as a function *f* of eight project performance attributes as shown below:

Project Performance = f (cost, schedule, profitability, cash flow, safety, quality, project team satisfaction, and client satisfaction).

In addition, the system forecasts expected performance at any time period and at completion. It also recommends a mechanism to select corrective action plans that lead to better project performance. In addition, the research proposes, as part of future research, the concept of a guide in a matrix form to resolve contradictions among the various performance indices. It also introduces the concept of agents to distributed performance management. Although the proposed concepts are intended for use by contracting companies during the construction phase, they can be adapted for use by any project-driven company during any phase of a project. The proposed work is innovative and utilizes some known mathematical theories like the Analytical Hierarchy Process for evaluating the overall project performance, the Dynamic Markov Chains for forecasting performance, and genetic algorithms for optimizing performance. Some other innovative methodologies like TRIZ, the theory for inventive problem solving (developed by the Russian scientist Genrich Altshuller) and the theory of intelligent agents are also used to introduce some related future work.

Although the proposed system is based on quantitative models, it does not eliminate the role of sound subjective judgment by users. All the proposed models are designed to incorporate user input and feedback. The main objective of the system is to supplement the user's knowledge and to help him take for efficient and effective decisions.

1.4 Need for an Integrated Performance Management System

There is currently no total performance measurement and management tool for construction projects although the literature contains many fragmented qualitative and quantitative models. Previous research has concentrated on developing models of a generic nature, which do not offer immediate solutions to practical problems faced by construction companies. The literature review reveals many studies that focused on the evaluation and forecasting of one or two aspects of performance (usually cost and schedule). These attempts do not address the concept of total performance management and the need to evaluate all aspects of performance like safety, quality, cashflow, and team satisfaction. Moreover, performance evaluation, forecasting, and implementation of corrective action, are not integrated in one model. Their natural succession and interdependency have not been addressed. In current practice, construction companies do evaluate and forecast the overall status of projects, which is vital for benchmarking, evaluation and strategic planning. As a result, there is a need for an integrated performance management system that can help contractors to effectively manage the performance of projects. The perception of failure and success of projects is currently based on subjective evaluations and there is an immediate need to develop a model that would allow management to formalize the way they evaluate projects. This research will try to address these issues by developing a set of integrated models as will be discussed in the next section.

1.5 Research Scope and Objectives

The main objective of this research is to develop An Integrated Framework for Evaluation, Forecasting and Optimization of Performance of Construction Projects. This research focuses on the construction phase of a project and is intended for implementation by contractors. The sub-objectives of this research are to develop the following tools and models:

1.5.1 Integrated Project Performance Evaluation Model

The proposed model enables construction managers to evaluate separately the performance of eight project attributes (cost, schedule, billing, profitability, safety, quality, team satisfaction, and client satisfaction) as well as the overall project success in a formal and systematic way. It helps users to identify and set relative weights for every attribute on the basis of their objectives, knowledge and experience, and project conditions. The proposed model does not under estimate the significance of the user's expertise and judgment in the decision-making process but tries to organize it. Consistent and quantitative measurement of performance leads to better variance analysis and consequently effective project control and achievement of project objectives. In addition, the model allows management to compare performance data among projects and to better plan for future projects.

1.5.2 Project Performance Forecasting Model

The Project Performance Forecasting Model is built on the assumption that performance is a dynamic and stochastic process. Towards this end, the model uses dynamic Markov chains and incorporates user feedback, historic trends, and latest project status to predict project performance.

The proposed method has the capability to incorporate judgmental feedback from experts to tune the final forecasted figures. It is believed that the project manager's talent or intuition is a significant factor that contributes to the project's success. This model formulates a firm forecasting strategy to compliment the project manager's expertise. It should be emphasized that experienced users should provide the input to the model in order to obtain reliable forecasts.

1.5.3 Performance Optimization Model using Genetic Algorithms

The Project Performance Optimization Model is an innovative approach to select a set of corrective action plans using genetic algorithms (GAs). Within the constraints discussed below and the limitations of genetic algorithms, the selected set of plans will be optimal or near optimal. The proposed framework is based on the project objectives hierarchy and the performance-forecasting model. Using a genetic algorithm methodology for total performance optimization, the model considers the actual performance status to-date and optimizes the performance at the end of project by determining the best combination of corrective action activities as specified by the user at that time.

It should be emphasized that the output of the model is a *computed optimal plan* based on the information provided by users and is not necessarily the *best plan* of action in the absolute sense. This is the fittest plan based on the model's assumptions and user's input, which is not necessarily the best solution for the problem at hand. This is due to the fact that in construction performance management there are many interdependent internal and external (e.g. client related) qualitative factors that are not easy to quantify or model but can have significant impact on the decision taken. For a plan to be feasible and effective, it must be assessed and modified (to accommodate other constraints) by the user. The proposed tool will only *assist* the decision-maker select a *better or improved* course of action and is never intended to completely replace human judgment.

1.5.4 Performance Conflict Resolution Framework

(TRAC) or, Techniques for Resolving Performance Contradictions, is a systematic procedure that helps decision makers to resolve performance contradictions among the competing project attributes. This tool transfers the process of project performance conflict resolution from an occasional and unorganized event into a regular and systematic project controls practice. Even the very experienced project manager could utilize this guide to expedite his search for a solution.

TRAC assumes that solutions to construction performance problems are derived from existing laws and principles in the field of project management and associated areas and that these principles can be re-used to solve new problems.

The objective of TRAC is to guide the user in his search for a solution and does not generate or guarantee a ready and workable solution. This guidance expedites the search and allows the decision maker to focus on the most promising and effective corrective action plans. The knowledge, experience, and judgment of the user (e.g. project manager) are needed to supplement the proposed framework and consequently the human element is vital for proper implementation of TRAC. It should be noted that this framework should be completed and validated as part of future research.

1.5.5 Agent-based Performance Management Framework

The proposed research will introduce an Agent-based Project Performance Management Framework (APPM) which formalizes and automates the complex process of communication, prioritization and optimization of corrective action plans so that the performance of a construction project can be controlled with the involvement of the project participants. The agent-based framework will be based upon a distributed coordination methodology, which allows all the concerned parties (cost, schedule, quality, safety, etc.) to view all aspects of performance and to evaluate the impact of their proposed plans on the overall project performance. Figure 1.2 shows the four components of research.

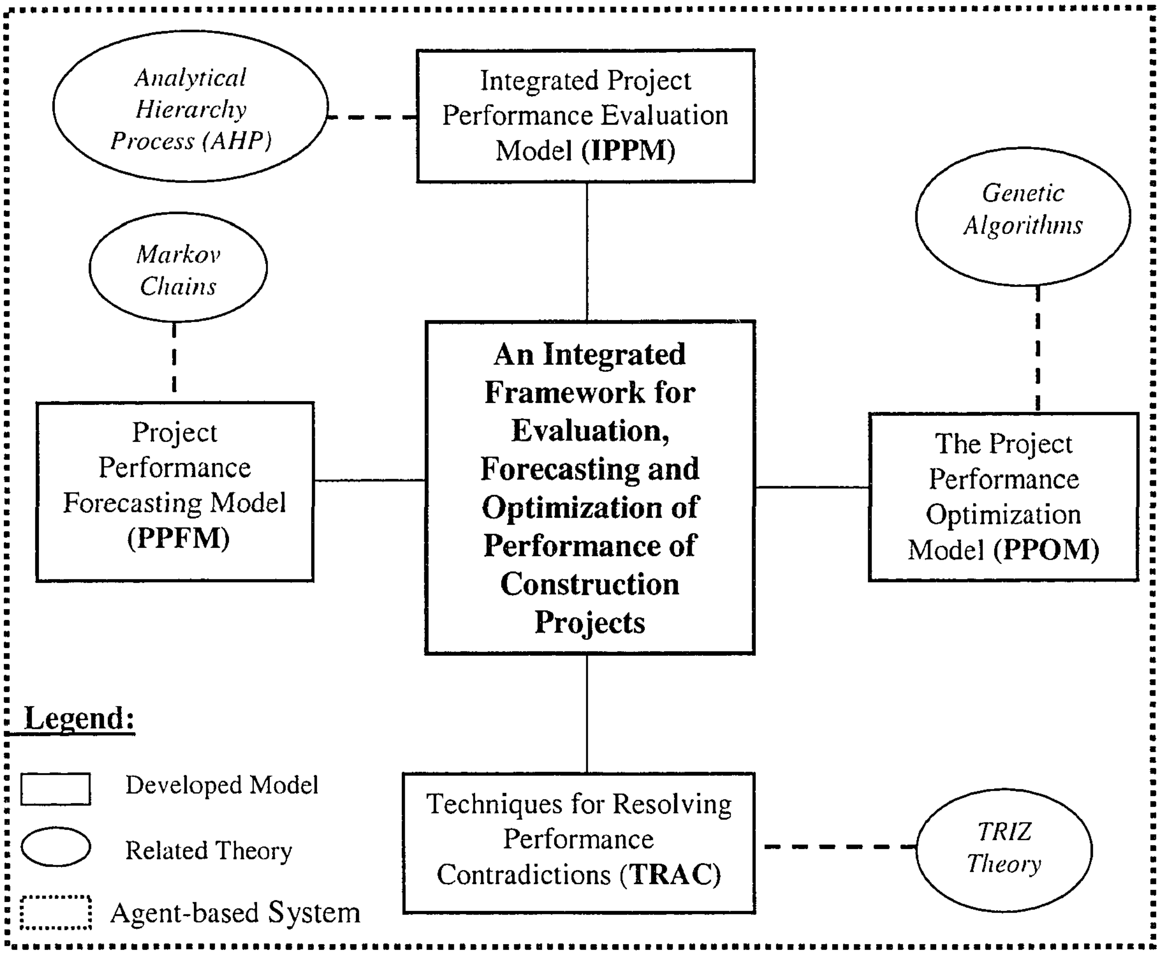


Figure 1.2 Summary of Research

1.6 User's Role and Competency

The role of the user is vital through out this research. The proposed models to evaluate, forecast, and optimize construction performance cannot produce reliable results without proper user input that is based on sound engineering judgment and past experience. This research assumes that the model users are competent and skilled since the model output is greatly impacted by the quality of input data. Moreover, the models presume that all project staff are competent; the model cannot identify issues of staffing deficiency.

For example, the user sets the priorities and the performance scale for every project objective in the performance evaluation model. The performance optimization model will assist decision makers by proposing a set of *effective* corrective action plans that are not necessarily the *best* plans. In many cases, decision makers will modify the plans, proposed by the model, to generate better plans when other external factors are considered. The real objective of the optimization model is to propose improved solutions to assist users in taking more informed and timely decisions.

Also, TRAC provides the methodology that leads project managers toward an effective solution for their problem and does not recommend or impose a specific solution. The algorithm *does not* replace the project manager but can assist him to accelerate the conflict resolution process.

As with any decision support tool, the proposed models can only lead to satisfactory results if the user's knowledge of the tool is satisfactory. In addition, the user must be competent and have good project/construction management knowledge.

1.7 Research Methodology

The strategy used in this research is based on developing a decision support tool for the construction manager for improved performance management. The methodology to develop such a tool uses mathematical and analytical concepts; and at the same time allows users to incorporate their input and provide feedback. The plan of this research consists of the following four phases:

Phase 1 - Literature Review: This phase involves literature review of the performance evaluation methods, forecasting methods, and performance optimization techniques that are applicable to construction projects.

Phase 2 - Concept Development: This phase establishes the concepts, criteria, processes, and procedures of the proposed performance management models. The concepts of distributed performance management and resolution of performance contradictions are also laid out.

Phase 3 – Mathematical Modeling: This phase involves the formulation of the mathematical criteria, functions and equations. The analytical models and framework architectures are constructed in this phase.

Phase 4 – Model Verification: The methods and results are verified and demonstrated through a functional prototype using data of a construction project carried out by a local contractor in Alberta.

1.8 Thesis Organization

The remainder of the thesis is organized into the following chapters:

Chapter 2 of this study is a description of a proposed framework for an integrated project performance system. This system will assist companies to evaluate the performance of construction projects in a quantitative and systematic manner. It also reviews the current literature related to performance measurement.

Chapter 3 contains a brief overview of the current forecasting techniques and proposes an innovative performance forecasting model using dynamic Markov Chains.

Chapter 4 presents a comprehensive model for total construction performance optimization using genetic algorithms. The proposed framework is based on the proposed project objectives hierarchy and the developed performance forecasting model.

Chapter 5 introduces the theoretical framework for two areas of related future work. The first part introduces (TRAC) or, Techniques for Resolving Performance Contradictions. TRAC is a guide that helps decision makers to completely resolve or minimize performance contradictions among the competing project attributes. The second part of this chapter introduces an Agent-based Project Performance Management Framework (APPM). This part discusses the application of the multi-agents systems (MAS) to the overall integration and interface among the evaluation, forecasting, and optimization models developed in this research.

Chapter 6 presents the conclusions of this research, listing its contributions as well as its limitations. This chapter also offers some observations as well as suggestions for future work.

Appendices A-Y demonstrate the application of the performance measurement and forecasting models through a case study based on an Airport Construction Project carried by a local construction company in Edmonton, Alberta.

REFERENCES

Christensen, D.S., (1994). “A Review of Cost/Schedule Control Systems Criteria Literature.” *Project Management Journal*, 25(3), 32-39.

Construction Industry Institute CII (1995) - *Pre-project Planning Handbook*.

Diekmann, J.E., and Al-Tabtabai, H., (1992). “Knowledge-Based Approach to Construction Project Control.” *International Journal of Project Management*, 10(1), 23-30.

Douglas III, C., (1993). “Field Project Control-Back to Basics.” *Cost Engineering*, AACE, 35(10), 19-28.

Moselhi, O., (1991). “Integrated Time and Cost Control of Projects.” *International Symposium on building performance*, January, Cairo, Egypt.

Nassar, N., Halepota, T., and AbouRizk, S. M., (2003). “Integrated Project Controls System – IPCS.” *Proceedings of the CSCE 5th Construction Specialty Conference*, Moncton, NB.

Russell, A.D., and Fayek, A.R., (1994). “Automated Corrective Action Selection Assistant.” *Journal of Construction Engineering and Management*, ASCE, 120(1), 11-33.

Framework for an Integrated System for Evaluation of Performance of Construction Projects – A Quantitative Approach

2.1 Introduction

The objective of construction planning and controls, a basic project management function, is to ensure a well-coordinated and successful project. A basic element of planning is the set-up of objectives. The objectives will guide the many decisions made during the project's life. These decisions involve trade-offs between schedule, cost, quality, and other performance attributes.

Effective monitoring of the progress of construction projects requires the integration and quantification of the various aspects of performance. The traditional performance indicators in the construction industry are completion time, cost and quality of construction. Most current project control systems measure quantitatively cost and schedule status and forget other major aspects of project performance like cash flow, profitability, quality, safety, project team satisfaction, and client satisfaction which are in some cases as important as cost and schedule. Very few project management systems quantify the later project attributes and they do so independently without proper integration to the overall project performance. The perception of failure and success of projects is usually based on personal indices and the experience of the project manager and it is not uncommon that two project managers would assess the performance of the same project using the same data differently (Rad 2003). The disparity of judgment is mainly due to the lack of a clear and consistent evaluation procedures and methodology. In some organizations, the perception of success of projects is based on some implicit and subjective criteria. In this unstructured project performance environment, project leaders often act based on their "gut feelings". It should be noted that this study does not eliminate the "gut feelings" role but attempts to supplement it with some rational and structured rules.

Obviously, project managers want to identify the impact that different decisions have on every aspect of performance as well as on the overall performance of projects. A great deal of effort is normally spent on accurately measuring some performance indices like cost and schedule where as the evaluation of the overall performance is carried out in a less structured or subjective manner. However, the overall project performance is a complex concept that changes with time and may differ for different project team members. In spite of the complexities involved, construction organizations need a method of measuring project performance based on available project data to forecast performance and compare outcomes across different projects.

There are many occasions where the project is under budget and progressing as scheduled. Yet it is considered a failure by upper management because of the low quality and safety performance records. Conversely, a project can be behind schedule and over budget and still be considered a successful one because it was completed with high quality, excellent safety record, and to the satisfaction of the client.

The objective of this chapter is to present an evaluation model/methodology where construction practitioners can use to assess project performance during the construction phase. This research proposes a framework to integrate the project performance and formalize the evaluation process by introducing eight performance indices. These indices cover: cost, schedule, billing, profitability, quality, safety, project team satisfaction, and client satisfaction. These eight performance areas are proposed based on the author's experience as project controls manager in the construction industry. Implementing this set of performance factors through out the project construction phase will provide consistent information that will enable project managers to measure all aspects of performance against a quantitative and explicit set of targets. Since the client and the project team view project success/performance differently another set of indices reflecting the client's preferences and priorities must be developed. For example, in lump sum projects, the client focuses on quality and safety more than on cost or profitability. This work describes the development of a project performance hierarchy from a contractor's point of view.

This study is proposing a generic project evaluation model from a contractor's perspective that is applicable to almost any project in the construction industry. It should be noted that the fundamentals do not change. Performance must be measured, forecasted, and enhanced in every project. The objective is neither to standardize the performance indices nor their priorities, but rather to establish a framework for consistent and quantitative evaluation process for performance of construction projects. Although the proposed hierarchy reflects to a great extent the contractors' preferences and can be used without major changes, it can be modified to suite the project contractual setup, the organizational culture and preferences, and the company values, strategic goals, mission and vision. In other words, the implementing construction companies need to match performance goals to project objectives, as most contractors perceive performance according to the projects goals and organization's objectives (Cole 1991).

The priorities for the performance indices are derived according to importance. This weighting of indices with respect to importance is a process of multi-criterion decision-making. The Analytical Hierarchy Process (AHP), developed by T. Saaty (Saaty 1982) is used to derive these weights. It should be noted that some other methods could be used to derive priority weights like fuzzy logic, and the Delphi Technique but need to be investigated prior to application. At least three reasons support the use of AHP in this study: first, the ability of AHP to incorporate the qualitative and quantitative factors involved in project evaluation that otherwise would be difficult to incorporate; second, the structure of the project performance hierarchy is identical to the hierarchical design of AHP; third, the ability of AHP to incorporate the experience and knowledge of project managers to define weights and priorities.

This research is unique because: (1) it deals with one specific project phase, namely the construction phase, (2) it is designed for lump sum type of contracts, and (3) the overall project performance is quantitatively determined. However, the methodology is generic and can be applied regardless of the project type or phase.

The chapter is divided into several sections. Section 2.2 reviews the performance evaluation methods published in the literature. Section 2.3 explains the concept of project performance and success. Section 2.4 presents the proposed project performance hierarchy and the characteristics of project objectives. Quantification of the performance indices is presented under section 2.5. The AHP-based methodology to derive weights is presented in section 2.6. The proposed mathematical model to evaluate project performance is developed in section 2.7. Section 2.8 discusses the concept of interdependence among the performance indices. An extension to the proposed model using range judgments is proposed in section 2.9. Section 2.10 outlines the advantages of the proposed integrated project performance evaluation model and finally a conclusion.

2.2 Performance Evaluation Methods: Literature Review

Construction performance evaluation methods are used to calculate the degree of success of projects from the contractor's perspective. The degree of success is related to the extent of deviation of the project attributes from the established control baselines. In the last three decades, a number of methods have been developed to evaluate the overall performance for better project controls. This section reviews the existing performance measurement methods and models published in the literature.

2.2.1 Performance Measurement Methods

Controlling a project is a highly complex task and is currently carried out using a number of independent systems or methods. The following is a brief description of some of these methods.

S-Curve based Evaluation Method

This traditional method uses the S-curve to monitor cost and schedule performances. The S-curves methods can take many forms such as the Standard S-curve, Single S-curve, Double S-curve, and the Superimposed Cost/%Complete S-curves (Li 2004). These methods that use the earned value technique are very popular within the construction industry as means to track progress.

PERT/Cost Method

The Program Evaluation and Review Technique (PERT) was first introduced to the industry by the US Navy in 1957 to support the development of its Polaris missile program. The initial focus of PERT was on the management of the schedule and on the probability of project completion. This method used simulation techniques and probability laws to measure the schedule performance. Later in 1962, PERT was upgraded to PERT/Cost for tracking cost also by adding resources to the network. Through this model, the earned value concept was first introduced to the industry as a project management tool (Fleming and Koppelman 2000).

Earned Value Method

In 1967, the US Department of Defense (DoD) issued their Cost/Schedule Control Systems Criteria, known as C/SCSC (Fleming and Koppelman, 2000). Currently, these criteria are known as the Earned-Value Management System (EVMS) criteria. This system is based on three S-curves, namely, the Budgeted Cost of Work Performed (BCWP), the Budgeted Cost of Work Scheduled (BCWS), and the Actual Cost of Work Performed (ACWP). The earned value is the value of the work completed in terms of the budget allocated to that work (Christensen 1994). The earned value system is briefly described under Section 2.4.4.

Barraza et al. (2000) proposed a new presentation of Stochastic S-curves (SS), as opposed to deterministic S-curves used by the Critical Path Method (CPM) and earned value techniques, to facilitate probabilistic monitoring of project performance using project progress as the independent variable. Using simulation, a possible progress-based S-curve is obtained for each simulation iteration. The set of all simulated S-curves defines what is named as stochastic S-curves. Since SS-curves provide probability distributions for budgeted cost and schedule for a given percentage of progress, project performance can be monitored by evaluating cost and time variations (CV and TV). CV and TV are obtained by comparing the expected budgeted cost and planned duration with actual to-date cost and elapsed time respectively. Although this approach is based on the earned value methodology, it has the advantage of incorporating the stochastic behavior of project activities by providing a range of likely outcomes for the project at any percent of its progress. This integrated S-curves method has also the advantage of using project progress as a performance variable in the graphical representation.

Discussion

The S-curve and PERT methods evaluate performance in terms of the cost and schedule indicators independently. They do not provide the decision maker with a comprehensive view of performance of all project aspects including but not limited to profitability, quality and safety. The Earned Value methodology, although used across the industry, only integrates cost and schedule. Other significant project objectives such as quality and safety are not integrated into the system and consequently must be controlled using other systems. In addition, the earned value method is deterministic and is limited with regard to its ability to address project variability.

2.2.2 Studies on Project Success Factors

Several papers have been written related to factors necessary for achieving success in construction projects. Success factors are different from success criteria. Success factors are those factors or procedures that impact the project outcome. Success criteria are the standards on which a decision regarding project success is based (Gibson and Hamilton 1994). It should be noted that the goal of this study is to identify and quantify the project performance indices or success criteria and the identification of success factors is beyond the scope of this research. Nevertheless, the study of the factors impacting the achievement of the project objectives is very important and that is why this topic has attracted the interest of many researchers and practitioners. The identification of critical success factors for the project objectives will help management allocate the limited resources of time and manpower in an efficient manner (Chua et al. 1999).

Many studies have only identified factors that contribute to construction project success using structured and unstructured research approaches. Many of the important success factors are related to the project team, planning and control. A detailed study on the relationships between project execution strategies and project performance can be found in the works of Jaselskis and Ashley (1991) and Alarcon and Ashley (1996). Both studies highlighted the significant role of planning, and project coordination. Other studies included project partnering (Larson 1995), the influence of management and labor on construction productivity (Lim 1993), the success of the traditional building process (Mohsini and Davidson 1992), and construction contracting methods (Gordon 1994).

Jaselkis and Ashley (1999) provided some useful management strategies for achieving construction project success in developing countries from the contractor's perspective. The study suggested that greater effort is required by the contractor to control a construction project in a developing country especially in the area of safety and quality. It also suggested that project managers working on successful projects in developing countries have more experience than their counterparts working on projects in developed countries. Pinto and Slevin (1992) identified ten critical success factors based on interviews with practicing project managers. Chua et al. (1997), using field data of project performance, developed a neural network model to identify the key management factors that affect budget performance. Eight major factors were identified in areas related to the project manager, project team, planning, and control efforts. Cheng et al. (2000) presented a framework to identify critical success factors that contribute to the successful use of partnering in projects. The factors identified in the framework are effective communication, conflict resolution, adequate resources, management support, mutual trust, long-term commitment, coordination, and creativity. Gao et al. (2002) developed a comprehensive list of factors leading to success of small projects based on data collected from active small projects personnel as well project success factors identified in the literature. The paper concluded that the factors on small projects are similar to those on large projects. The following is a partial list of papers that have provided insight into some critical factors for achieving overall project success, (Kothari 1986; Murphy et al. 1974; Cleland 1986; de Wit 1986; Jolivet and Batignolles 1986; Morris 1986; Ashley et al. 1987; Pinto and Slevin 1988). It should be noted that most of the above mentioned studies used the experience of project managers and/or field data to derive the success factors.

2.2.3 Performance Measurement Models

Far fewer papers found in the literature review address the concept of integration of performance measurement of construction projects. Construction researchers handled performance evaluation problems through various measurement systems. The systems were found to be falling within three major categories: single attribute measurement, multi-attribute measurement, and measurement of organizational effectiveness. The following is a summary of some methods found in the literature.

Single attribute measurement systems

Many construction performance methods involve a single attribute to measure the success of a project, most of which are related to labor productivity. There has been evidence of continuous research in an attempt to improve the single attribute measurement systems through more systematic and focused approaches (Thomas and Kramer 1988, Randolph and Raynar 1997). Some of these improved models have developed using modern computer based techniques like mathematical analysis, neural networks, and genetic algorithms (Chao and Skibniewski 1994, Flood and Nabil 1994, Boussabaine 1995, Boussabaine and Duff 1996, Portas and AbouRizk 1997). Although the measurement of labor productivity is very significant at the operations level, it is less beneficial at a higher level where management needs to monitor all aspects of performance.

Multi-attribute measurement systems

Single attribute measurement systems might not properly reflect the true health of construction projects in a broader sense. To overcome this drawback, multi-attribute measurement systems have emerged which enable users to monitor more than one aspect of effectiveness within a project. The following papers addressed multi-attribute performance measurement.

Ashley et al. (1987) measured success of construction projects using six performance measures: (1) budget performance, (2) schedule performance, (3) client satisfaction, (4) functionality, (5) contractor satisfaction, and (6) project management team satisfaction. The major limitation is that only two criteria are objective, the other four are subjective.

Freeman and Beale (1992) identified seven common criteria of success: (1) technical performance, (2) efficiency of project execution, (3) managerial and organizational expectations, (4) personal growth, (5) project termination, (6) technical innovativeness, and (7) manufacturability and business performance. In this model, the calculation of project success, using economic analysis, is sophisticated and requires information that may become available many years after completion of construction.

Alarcon and Ashley (1996) presented a methodology for the evaluation of project performance based on construction experts' knowledge and project team experience, decision analysis techniques, and cross-impact analysis. The model captures four performance measures: cost, schedule, value to owner, and effectiveness or how well the project went into full production. It is obvious that the model combined contractor driven objectives (cost and schedule) with client driven objectives (value and effectiveness). The model limitations arise from the many assumptions made by experts and from its simplified structure that only includes a limited number of variables.

Tan (1996) identified three criteria of success for technology transfer projects: (1) overall performance, (2) recipient satisfaction, and (3) satisfaction with the transfer process. All the adopted criteria are subjective in nature.

Sinthawanarong and Emsley (1998) presented a model for contractor's on-site performance evaluation. The model integrated eight performance indicators associated with four key indicators (cost, time, quality, and safety) established through literature surveys. Although the model proposed integrating the indices to form one overall index, it did not present a methodology for integration. It suggested that users specify, using a set of questions, a degree of significance of each index with respect to construction performance.

Chua et al. (1999) presented a hierarchical model for construction project success consisting of three project objectives, namely, budget, schedule, and quality. Sixty-seven critical factors addressing budget performance, schedule performance, quality performance, and overall project success are identified. The analytical hierarchy process was adopted to determine the relative importance of success related factors. The relative importance of the three objectives of construction project success was also calculated using AHP and were almost of equal significance. The calculated weights are 0.314, 0.360, and 0.325 for budget performance, schedule performance, and quality performance respectively. The study did not explain how to measure the three objectives and did not incorporate critical project success criteria like safety, and client/team satisfaction.

Griffith et al. (1999) presented a total of 52 success variables and developed, with the assistance of 15 industry practitioners, an index to measure the success of industrial project execution. This index is comprised of four variables: budget achievement (B), schedule achievement (S), design capacity (C), and plant utilization (U). The budget achievement is measured by percent deviation at project completion from the project authorization budget. The schedule achievement is measured by percent deviation at project completion from the project authorization schedule. Design capacity is defined as the nominal output rate (e.g. tons per year) and is measured by the percent of design capacity planned at the time of project authorization that was actually attained after 6 months of operation. Plant utilization is defined as the percentage of days in a year the plant actually produces product and is measured in the same manner as design capacity. The study reclassified the success variables into a common measurement system in order to combine all four indices to form one success index equation. The authors combined the variables with their associated weights to obtain the following weighted equation:

$$\text{Success Index} = 0.35B + 0.25S + 0.28C + 0.12U. \qquad \text{Equation (2.1)}$$

The limitations of the study arise from the following four areas:(1) The index does not address the success of all aspects of a construction project as it does not, for example, include quality and safety as performance measures. (2) The generalization of the success index equation, using a selected number of large industrial projects, is not correct. The success index may not be applicable to small projects or projects in other industries. The methodology can be generic but not the weights as each project has its own weights. (3) The weights were derived from the frequency of responses by the interviewees to a generic question without checking the validity and consistency of the answers. This may result in some kind of bias in the weights. (4) The success equation mixed construction-related performance indices with design and operations success variables. (5) Due to the limitation in (4), the success index can measure performance only after six months of facility operation. This will be of minimal benefit to the project team who needs to monitor performance through out the construction phase.

Turner (1999) stated that there are five project objectives that need to be managed. These are: (1) project definition and scope, (2) project organization, (3) project cost, (4) project schedule, and (5) project quality. He suggests that time, cost, and quality are constraints and are influenced by the project scope and organization.

Cheng et al. (2000) stated that the degree of success of partnering could be determined by objective and subjective measures. These measures are: cost variation, rejection of work, client satisfaction, quality of work, schedule variation, change in scope, profit variation, safety measure, rework, litigation, and tender efficiency. The study did not indicate how to evaluate and weigh these measures.

Gao et al. (2002) identified four criteria of success based on findings from a survey analysis and interviews. These criteria are cost, schedule, technical performance, and client satisfaction. The study lacked quantification of the success criteria.

Rad (2003) argued that the perception of failure and success of projects is usually based on subjective evaluations and presented a model that would allow the project team and the client to formalize the way they evaluate projects. Given that the client and project team generally view project success differently, the model proposes two different sets of attributes or success indicators. The author proposed six success indicators as viewed by the client, namely; scope, quality, schedule, cost, team morale, and client satisfaction. The success attributes, as viewed by the team, were derived from the limited project management activity categories that should receive careful and continuous attention. These success factors are: scope, quality, contract, change, team, and client. Both sets of factors are different because the former is focused on the deliverables and the later is focused on the means by which the deliverables are achieved. The generalized project success evaluation model has two shortcomings: (1) the model does not show how to quantify the various indices, (2) the model assigned points to each success attribute to indicate its relative importance in a subjective manner. It did not offer a quantitative and systematic approach to determine the weights.

Shields et al. (2003) presented a metric for measuring the success of the construction phase of projects. This metric is different from the other metrics because it deals with a single project phase and is quantitatively derived. Using data from 209 North American industrial projects, the study presented an empirical equation for calculating the success of the construction phase on a scale of 1-10. This research hypothesized that construction phase success can be expressed as:

$$\textit{Construction Phase Success} = f\,(\textit{Cost, Schedule, Quality, Safety}) \qquad \text{Equation (2.2)}$$

The first term is represented by the cost growth (CGS) and is defined as:

$$\frac{\textit{Actual Construction Phase Cost} - \textit{Initial Predicted Construction Phase Cost}}{\textit{Initial Predicted Construction Phase Cost}}$$

The construction schedule growth (SGS) is used to represent the second component and is defined as:

$$\frac{\textit{Actual Construction Phase Duration} - \textit{Initial Predicted Construction Phase Duration}}{\textit{Initial Predicted Construction Phase Duration}}$$

The third component is quality and it is represented by the rework factor (RFS), which is defined as:

$$\frac{\textit{Total Direct Cost of Field Rework}}{\textit{Actual Construction Phase Cost}}$$

The fourth component is safety and is represented by the lost workday case incident rate (LWCIRS), which is defined as:

$$\frac{\textit{Number of Lost Workday Cases x 200,000}}{\textit{Site Craft Work hours}}$$

The study associated the four components of success with the major cost overruns during the construction phase of a project. As a result, it used the cost ratios to determine the weight of the construction phase success equation, which is given as:

$$CPS = [c_1 / c_T]CGS + [c_2 / c_T]SGS + [c_3 / c_T \; RFS + [c_4 / c_T]LWCIRS \quad \text{Equation (2.3)}$$

Where c_1 is the cost of the average construction phase cost growth, c_2 is the cost of the average construction phase schedule growth, c_3 is the average rework factor cost, c_4 is the cost of the average number of lost workday case incidents, and c_T is the total cost.

Using some assumptions to calculate the costs, and rounding the weights, the CPS equation was presented as follows:

$$CPS = 0.4\ CGS + 0.25\ SGS + 0.3\ RFS + 0.05\ LWCIRS \qquad \text{Equation (2.4)}$$

The study has the following four drawbacks: (1) the equation did not address the people-related success variables such as project team and client satisfaction. (2) The weights for the four variables were based on the cost ratios, which is not always true and could vary from one project to another. (3) The study made assumptions that could apply only for very few projects in certain geographic locations, like the cost for each lost workday incident is $200,000. (4) Using the developed equation, the evaluation of success could only be calculated after the completion of the project when it is too late for corrective action.

Rozenes et al. (2004) proposed a Multidimensional Project Control System that utilizes the yield concept to evaluate the performance of projects. The yield is calculated at the control work package level, using vector presentation, to measure the performance of eight subjects grouped under two categories. The *functional* category includes: configuration management, system safety, integration, value engineering studies, and life cycle cost analysis. The *operational* category consists of: preliminary requirements, system/cost analysis, effectiveness analysis, and logistics support analysis. The study presented the overall project performance by means of the Gap Performance index GP. This index presents an overall evaluation of the gap existing between the planned and actual performance. The research indicated that the optimal value of GP is zero and in order to improve the performance of the project, the project manager must take corrective action to reduce the value of GP. The major weaknesses of this approach are that firstly: the weights assigned to the eight subject areas are very subjective. Secondly, the level of performance is not quantitatively derived and is left for the project manager to define.

Organizational effectiveness measurement models

Good team performance has been proved to be a critical factor in the success of project-driven organizations like construction companies. Accordingly, project goals should reflect the ultimate goals and values of the organization as well as the satisfaction of the people responsible for the overall success of the project. Researchers have presented various models about construction organizational effectiveness (Dias and Ioannou 1996, Handa and Adas 1996).

2.2.4 Discussion

Based on the papers reviewed, it is obvious that there is no universally accepted definition or measurement of overall project performance. Yet, most papers agree that performance measurement is a complex and dynamic process. Despite these obvious difficulties, an objective measurement is needed to: (1) forecast performance at any future and at project completion as will be explained in Chapter 3, (2) evaluate the impact of specific corrective action plans on the project outcome as will be explained in Chapter 4, (3) make comparisons between performances of different projects. Based on the limitations associated with the previously mentioned methods, there is the need for a relatively simple but comprehensive and structured performance measurement model.

2.3 Concept of performance success in this research and methodology

The definition of performance in this research is the achievement of both efficiency and effectiveness with regard to all project objectives. In other words, the development of a project evaluation model should integrate quantitative as well as human-related goals, both of which have significant influences on the overall project success. In this research, a project is said to be successful if it is perceived by the construction organization to have outstanding results for all parties involved in the project.

The research methodology used in this chapter includes four steps: (1) identification of the project objectives and performance hierarchy; (2) quantification of the performance indices; (3) normalization of the indices; and (4) integration of the various performance indices to develop an overall project performance function.

2.4 Project Performance Hierarchy

The Construction Industry Institute (CII) Project Organization Task Force considers the objective-setting process as a critical element to the success of projects (Rowings et al. 1987). The same study indicated that on projects experiencing difficulties, the objectives lacked definition, clarity, and consistency. Also, the project team leaders did not have the same priorities or objectives. Identification, evaluation, and selection of the project objectives are the first and most important step in planning (Pinnell 1980).

2.4.1 Objectives or goals

Objectives are essential to the concept of project management (Pinnell 1980). Objectives or goals provide the project management team with a sense of direction by focusing attention on priorities. A structured goal hierarchy for a project:

- Provides an analytical platform for decisions and corrective action plans.
- Provides a clear and direct method of communicating objectives.
- Serves as a basis for project performance evaluation.
- Provides a rationale for the quantification of the overall project performance.

An objective emerges from a project performance area when the goals to be accomplished are specific. Clear and well-defined objectives are an important management tool. Two out of thirteen attributes that characterize an effective planning system are "clear statement of objectives" and "quantification of goals" (Dyson and Foster 1983). Project objectives are specific end results that have to be attained within a certain period of time (Mali 1986). Project objectives must be: clear and specific (not general), tangible and defined in terms of measurable results, realistic and attainable, approved by management to act as baselines, have clear responsibility and time component. Figure 2.1 shows the criteria that every project goal should have.

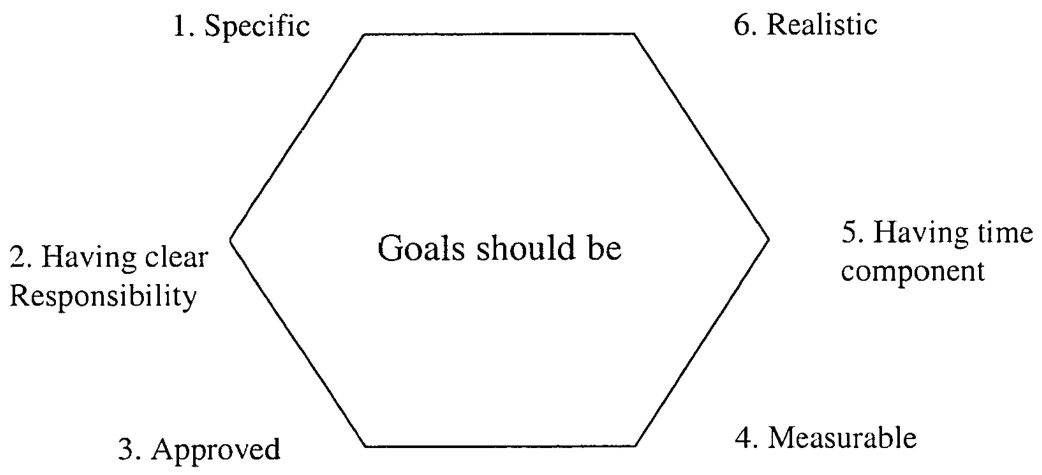


Figure 2. 1 The six criteria for project goals

Without objectives it is difficult to measure results and performance against prior expectations and the project leader may not have any idea of whether the project is on the right track.

Since project objectives must be consistent with the policies and procedures of the organization, the objective setting process for construction projects is an extensive exercise that involves many functional departments within the contractor's organization. Some of the areas that are usually part of the objective setting process are: operations, quality, safety, cost/schedule control, human resources, and finance. Once the project objectives are set, sub-objectives are defined in order to track the variance in each main objective. After the objectives and sub-objectives have been established, it is important to quantify and scale them as will be shown in the next sections. This will enable management to monitor progress for any specific project objective during the project's construction. Note that project objectives are not independent variables. Each objective has a positive or negative effect on the others, and it is extremely difficult to arrive at the right balance. It should be emphasized that the project objectives from the owner perspective are different from the project management point of view and a real project success is when both types of objectives are achieved.

In addition, executive management needs to support the project objectives and needs to motivate those who will achieve them. This is best accomplished by developing the project objectives at upper management level with input from the various functional areas of the company. This will ensure that the project objectives are in line with the overall company goals. During the execution phase, the project management team should review the performance indicators periodically, analyze any overruns, propose, and implement corrective actions. It is the ultimate responsibility of the project manager to make sure the project objectives are communicated and accomplished.

2.4.2 Communication of Objectives

Setting up a hierarchy of objectives and priorities for a construction project is necessary but not sufficient. The project objectives need to be communicated to all participants through a set of mechanisms. Rowings et al. (1987) identified two categories of mechanisms: primary and reinforcing. Primary mechanisms are used to directly communicate objectives to project participants and can include items such as:

- Scope of Work
- Contract clauses
- Policies and procedures
- Written objectives and priorities

Primary mechanisms are vital to project success, but alone, would not guarantee the success of a project. Reinforcing mechanisms will maintain focus and will support the communication of objectives and priorities in an indirect manner. These mechanisms give project leaders the opportunity to clarify the objectives. The following is some of the reinforcing mechanisms identified by Rowings et al. (1987):

- Weekly progress meetings
- Progress reports
- Safety reports

- Project instructions
- Cost and schedule reports
- Toolbox safety talks
- Upper management reviews

The objectives of the project must be made known to all project personnel and team leaders at every level of the organization (Kerzner 1989). If the project goals are not timely and accurately communicated, then it is entirely possible that functional managers and project leaders may all have a different understanding of the ultimate project objective, a situation that generates conflict among competing objectives.

2.4.3 Identification of Construction Performance Objectives

Most construction organizations look only at the time and cost parameters. If a schedule slippage or cost overrun occurs, then project managers will identify the cause of the variance. Looking only at time and cost performance might identify immediate contributions to profit, but will not tell whether or not the project itself was managed properly. Construction project success is often measured by the evaluation of three parties: the project team, the construction organization, and the client's organization. The assumption here is that a construction project cannot be considered successful unless it is recognized so by the three groups. This study presents a hierarchy of construction performance objectives that takes into account all success factors as viewed by the major players. The proposed goal hierarchy is *systematic,* and *flexible* enough to handle specific project requirements. The reader should realize that although project procedures can vary from project to project, project policies are usually similar in nature and do not differ between projects.

The project performance attributes, as viewed by the project team within a contracting company, are derived from the project management processes that receive close monitoring and control from the project team. The methods by which the constructors combine their specific project objectives with the owner's objectives are also important.

If the client views the timely completion of the project as very critical, then schedule performance objective should be closely monitored by the contractor and given high priority. The proper management of the activities contributing to these factors is a must for the project to succeed regardless of the nature or phase of project. However, the time spent on these activities might change through out the project life cycle. Figure 2.2 depicts a project performance hierarchy that forms the structural foundation for a formal construction performance evaluation system. In determining the performance indicators, the author's experience with a major construction company served as guidance in selection. Some modifications may need to be implemented, as mentioned earlier, to reflect the priorities and goals of the implementing organization and/or meet specific project requirements. The availability of quantified project indices will enable the project manager to benchmark his project against the established company baselines and ultimately improve the probability of achieving the project goals.

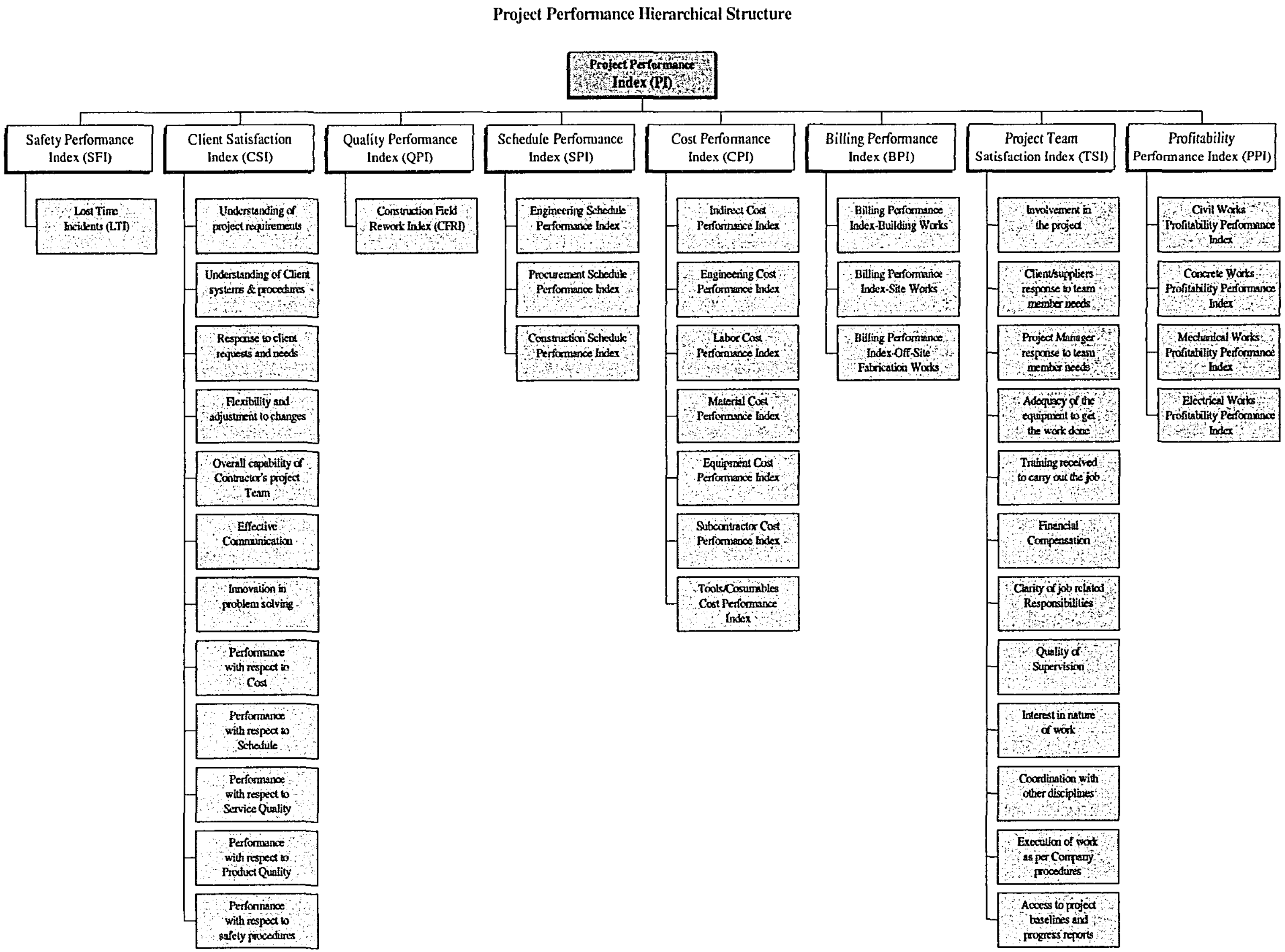


Figure 2. 2 Hierarchy design for the Project Performance Model

In the present study, project success is the ultimate goal. The eight proposed objectives are the criteria to achieve this goal. The first level of the performance evaluation hierarchy is the overall project performance index. The second level is a set of eight indices covering cost, schedule, billing, profitability, safety, quality, team satisfaction, and client satisfaction. The first six of these indices can be quantified but the last two are not easy to measure since they involve human and subjective elements. It should be noted that the measurement and quantification of people related issues is very subtle. Nevertheless, these performance indices have a major impact on the success of projects. A non-satisfied client will decrease the chance of getting future projects from the same client. Also, keeping the project team satisfied is critical to any project, since a company is as good as the people working for it. The priority weights assigned for these indices are dependent on many criteria that are project specific as well as company related such as corporate objectives and culture. In a way, these eight attributes could be considered as significant to all construction organizations executing lump sum contracts. The AHP approach will be used to derive these weights as will be shown in section 2.7.3. The third level indices would cover the details needed to calculate the second level indices. The hierarchy design for the project performance model is shown in Figure 2.2 and the definition and measurement of the various indices are presented in section 2.5.2.

2.4.4 Earned Value Method

The earned value concept was originally developed in the early 1900's by industrial engineers in factories but it was formally introduced as part of schedule/cost systems in 1962 (Fleming and Koppelman 1994). In 1967, the US Department of Defense issued its Cost/Schedule Control Systems Criteria known as (C/SCSC) which incorporated the earned value concept. In 1993, Australia, Canada, Sweden, and the USA established the International Performance Management Council to internationally promote the earned value technique (Abba 1995). In 1995, the National Security Industrial Association (NSIA), representing the private industry in US, standardized and modified the earned value criteria to better suite the project management community. The new standard is what is currently known as the Earned Value Management System (EVMS) (Fleming and Koppelman 1998).

Earned Value (EV) "is *a method for measuring project performance*" (PMI 1996). As per Goldfayl (1995), EV is "*a technique for integrating time and cost in a project, which takes into account actual performance against planned performance*". In order to apply (EV), a Work Breakdown Structure (WBS) defining the total project's scope of work, time and cost baselines, and actual results (actual expenditure and progress) are required to evaluate performance of any project.

Based on above, Earned Value (EV) is a classical project control method used for measuring two project objectives: schedule and cost. However, using the (EV) methodology is not sufficient, as project monitoring in this study requires more than the two dimensions of cost and time. In this research, two new indices, namely the billing, and profitability performance indices are calculated using the earned value concept as will be explained in the next sections. The Earned Value Management System (EVMS) is a technique that can be applied, at least in part, to the management of all capital projects, in any industry and employing any contracting approach (Fleming and Koppelman 2002). The use of earned value concept on construction projects, large or small, cost plus type or lump sum type, is widespread due to its benefits and ease-of-use. The earned value concept is based on three dimensions of cost data (Fleming and Koppelman 2002). These dimensions are:

- The Scheduled Value (SV), which is the budgeted cost or hours scheduled.
- The Earned Value (EV), which is the budgeted cost or hours for the actual work done.
- The Actual Value (AV), which is the cost or hours incurred to complete the actual work.

The above three dimensions apply to all construction projects although the actual value dimension is not easily calculated particularly in lump sum type of projects. Using the three dimensions of earned value, one can, perhaps as early as 15 percent complete (Fleming and Koppelman 2002), measure and monitor both the schedule and cost performance achieved to-date against the project baselines. If the results are below target, the project manager can implement corrective action plans to keep performance within the objectives set by management. Performance measurement should be carried out at regular intervals, preferably weekly. Currently, (EVMS) is widely accepted as an integrated project control tool in public as well as private projects.

One of the benefits of the earned value concept is its ability to forecast the project cost and duration at completion. A review of the various forecasting methods using the earned value concept is presented in Chapter Three.

For detailed discussion on the earned value concept the reader is referred to Christensen (1994) and to Fleming and Koppelman (2002).

2.4.5 Frequency of Performance Measurement and Control

As mentioned earlier, the project control cycle consists of: (1) measurement of the actual performance status, comparison to the baseline, (2) forecasting and analysis of the deviations, and (3) implementation of corrective actions in case of negative variances. Measurement is a critical step in the control process since it provides input to the forecasting and analysis tasks. One of the key issues that need to be considered when designing a control system is *how often* actual performance should be measured. The literature provides some general guidelines in this regard. Bent, in Cleland and King (1988, p. 579), differentiates between small projects (< 100,000 hours) requiring control on a monthly basis, and large projects (>1,500,000 hours) requiring control on a weekly basis. Meredith and Mantel (1995) argue that the frequency of control should be linked to the occurrence of events, and not only to the project calendar. Turner (1993) states that the frequency of reporting progress depends on the length of the project, the stage of the project, the risks involved, and the organizational level of the report recipient. Raz and Erel (2000), using a dynamic programming approach, determined the optimal timing of project control points by maximizing the amount of information generated by the control points. De Falco and Macchiaroli (1998) proposed a quantitative model to determine the timing of monitoring and control. The model is based on the definition of an effort function that is defined as a non-linear function of the total number of active operations and the total slack time.

Although all the above propositions could be true, this research assumes control points that are equally distributed throughout the project duration. In Chapter (3) the forecasting model is based on 20 reporting periods, and it is up to the organization to weigh the costs and benefits and decide on the optimal number of control points. In other words, this parameter is not a constant but varies with every project.

2.4.6 Control Baselines

The control baselines are also known as planned S-Curves, which are developed by allocating a certain resource (e.g. man hours, cost, and revenue) to the detailed control activities of a time-phased schedule. For example, using the project budget and schedule, a plot of cumulative budgeted cost, as a function of time, can be generated. Cumulative cost curves are commonly called cost "S-curves" because they resemble the shape of the letter S (the rate of work and consequently cost is low at the early and late stages of construction and high in the middle stage). Plotting the BCWS, ACWP, and BCWP as a function of time will also generate S-curves. Similar S-curves for man-hours and revenue can be obtained by plotting man-hours and revenue as a function of time. A baseline schedule that is realistic is pre-requisite for effective project controls (Moselhi 1991). A typical bar chart schedule, histogram, and S-curve are shown in Figure 2.3.

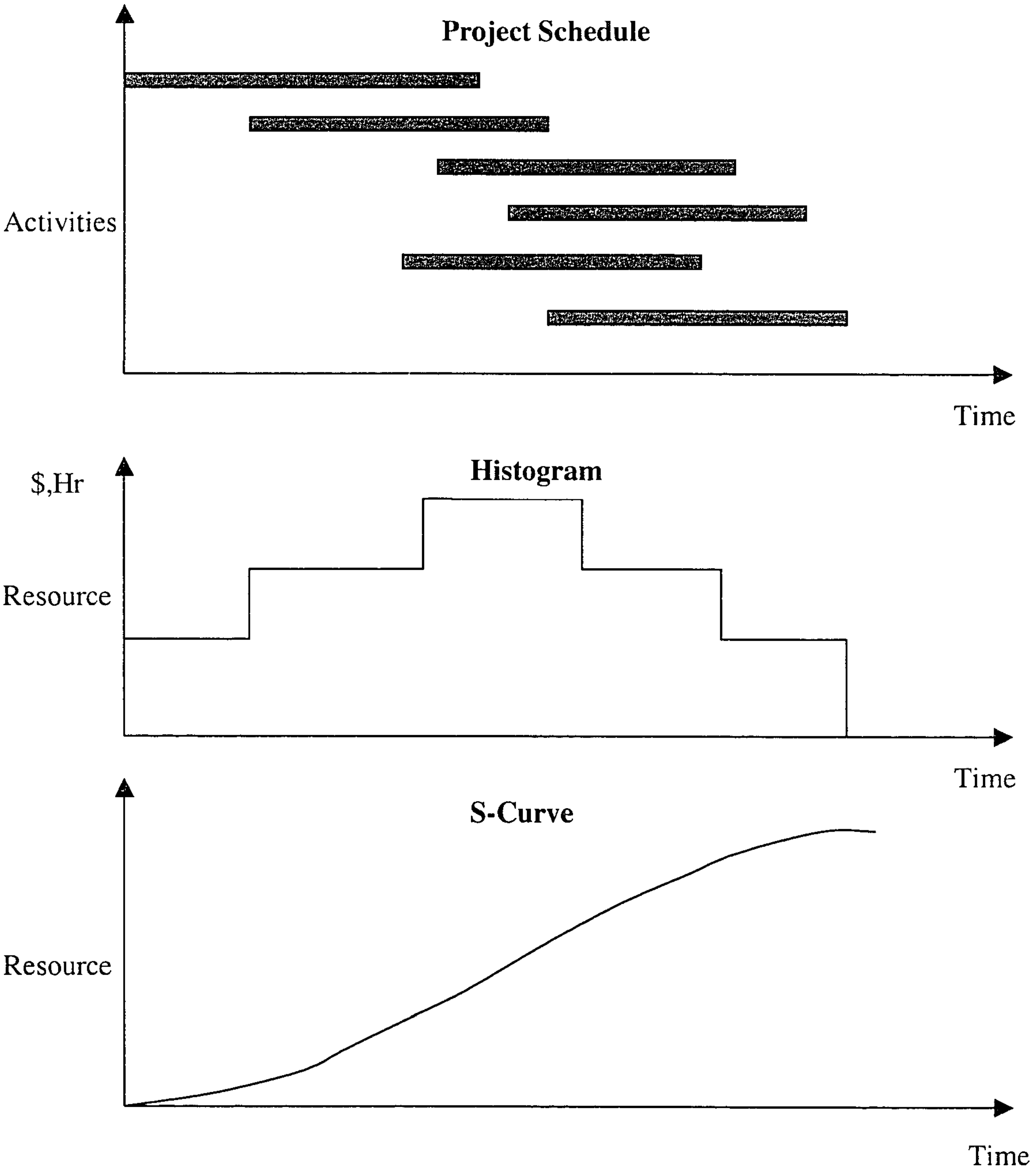


Figure 2. 3 Project Control Baselines

2.5 Quantification and Normalization of the Project Performance Indices

Before an organization sets up the performance indices hierarchy, it is necessary to develop an understanding of the multi-dimensional nature of performance. Indicators of construction success must be identified, understood and agreed upon by the project management team. Each performance index needs to be: (1) quantified, (2) normalized or measured to a standard scale, and (3) prioritized.

2.5.1 Measurement of Project Success: A Challenge

Measurement of project success is a real challenge and quite a complex task. Performance measurement is also a must for all organizations executing any type of projects because if it cannot be measured, it cannot be improved upon. The above literature review revealed that many researchers attempted to measure project performance. Some authors have emphasized the fact that evaluation of project success is a subjective measurement that can change over time and depends on who is evaluating the project (Morris and Hough 1987). A highly successful project for a designer may be a complete failure for a contractor. Some other researchers have indicated that the task of measuring project success in solely objective terms is impossible (de Wit 1986; Morris 1986). The complexity of measurement of performance is due to the following facts:

- Project objectives are dynamic in nature and change over time.
- Many project participants representing various interests are involved in defining and prioritizing the project objectives.
- Some of the desirable objectives are subjective in nature.

Most of the reviewed studies in the literature focused on either qualitative or quantitative measurement of performance. This research will present a model that measures both types of project attributes during the construction phase of the project in a structured and quantitative manner.

2.5.2 Project Performance Indices

Traditionally, cost, schedule, quality, and safety are the objectives considered as the most critical to the success of construction projects. The proposed research identifies eight performance indices and presents a methodology to measure the overall performance index. The development of the eight indices to measure the success of projects evolved from the author's experience in the construction industry and from literature review. The performance indicators represent efficiency in terms of cost, time, billing or cash flow, profitability, safety, quality, team satisfaction, and client satisfaction. Each of these eight indices is quantitatively determined and transformed into a standard scale as will be shown below:

1- Cost Performance Index (CPI)

The Cost Performance Index (CPI) is a measure of the cost efficiency of the project. The CPI is determined by dividing the earned value by the actual costs incurred. Any value of CPI < 1 indicates that costs are overrun. For example, a CPI of 0.85 indicates that for every dollar spent; only 85 cents of value is earned and consequently 15 cents are lost. The CPI is given by:

$$CPI = BCWP/ ACWP \qquad \text{Equation (2.5)}$$

Where,

BCWP = Budgeted Cost of Work Performed. It is the budgeted amount of cost for work-completed to-date or the cost allowed (based on budget) to be spent for the actual work done.

ACWP = Actual Cost of Work Performed. It is the cost incurred to complete the accomplished work to-date.

The values for the BCWP and ACWP used to calculate the CPI in the above equation are cumulative and include all project work up to the current data date.

An accurate measurement of the BCWP will enable contractors to pay their vendors and sub-contractors for only the actual work accomplished. This is a good way to mitigate financial risks on fixed-price or lump sum construction work.

The cost variance V_c, is the difference between *what was earned* (BCWP) and *what was incurred* (ACWP). For example, 50% of the project budget may have been expended to accomplish only 25% of the budgeted work. In this case, the project is over budget. V_C is represented as:

$$V_C = \text{BCWP} - \text{ACWP} \qquad \text{Equation (2.6)}$$

A positive V_C (CPI >1.0) is desired because it means that the actual cost of work performed is less than the budgeted cost of the same work and therefore the project is under budget. Critical variances are reported to management for further analysis and corrective action.

A cost variance is due to change in projected output quantities and/or change in cost per unit of output. Cost variances are negative when cost exceeds budget. Negative variances are unfavorable. The change in unit cost is a rate change, due to change in cost per unit of resource and/or change in productivity of resources. Each of these changes will produce a variance. For example, the material cost variance and the material cost performance index (CPI_M), vary due to differences between the budgeted unit cost of material and the actual unit cost and/or differences between the budgeted quantity of material and the actual quantity. Likewise, the labor cost variance and the labor cost performance index (CPI_L), vary due to: (1) the difference between budgeted and actual labor productivity, (2) the difference between budgeted labor rate and actual labor rate, (3) the difference between budgeted scope of work and the actual scope.

CPI is calculated for the project as a cumulative value to reflect to-date cost data. Although the project cost rating in Table 2.1 can be applicable to some projects, it is proposed for illustration purposes only and needs to be modified for every project. Since construction projects are unique in nature, performance-rating tables are unique to every project and must reflect the specific conditions and the cost control philosophy of the project.

Table 2. 1 Cost Performance Rating Table

Condition	Rating	Index Range
A	Outstanding Performance	$I > 1.15$
B	Exceeds Target	$1.05<I<= 1.15$
C	Within Target	$0.95<I<= 1.05$
D	Below Target	$0.85<I<= 0.95$
F	Poor Performance	$I <= 0.85$

The CPI is further divided into the following cost sub-indices as shown in level 3 of Figure 2.2. Each of these sub-indices is calculated by dividing the earned value by the actual value.

- Indirect Cost Performance Index (CPI_I).
- Engineering Cost Performance Index (CPI_E).
- Labor Cost Performance Index (CPI_L).
- Material Cost Performance Index (CPI_M).
- Construction Equipment Cost Performance Index (CPI_C).
- Subcontractor Cost Performance Index (CPI_S).
- Tools/consumables Cost Performance Index (CPI_T).

For example, the Labor Cost Performance Index (CPI_L) is calculated using Equation (2.7).

$$CPI_L = BCWP_L/ACWP_L \qquad \text{Equation (2.7)}$$

Where;

$BCWP_L$ = Budgeted Labour Cost of Work Performed, or the budgeted labour cost for the actual work done.

$ACWP_L$ = Actual Labour Cost of Work Performed, or the labor cost incurred for the actual work done.

The above analysis can indicate if the cost overrun is labour related. In case of negative cost overrun, further analysis should be carried out to identify the causes for such a variance. The labour cost variance can be further broken down into three components: (1) variance due to labour productivity, (2) variance due to labour cost rate, and (3) variance due to labour hours.

2- Schedule Performance Index (SPI)

The Schedule Performance Index is a measure of the schedule efficiency of the project; the SPI is determined by dividing the earned value by the scheduled value. Any value of SPI < 1 indicates that we are running behind schedule. For example, a SPI of 0.85 indicates that for every dollar of work we planned to do; only 85 cents of work is earned and consequently the project is 15% behind schedule by Cost. The SPI is given by Equation (2.8):

$$SPI = BCWP/ BCWS \qquad \text{Equation (2.8)}$$

Where:

BCWP = Budgeted Cost of Work Performed. It is the budgeted amount of cost for work-completed to-date or the cost allowed (based on budget) to be spent for the actual work done.

BCWS = Budgeted Cost of Work Scheduled. It is the budgeted amount of cost for work scheduled (as per budget) to-date.

The schedule variance V_S, is the difference between *what was done* (BCWP) and *what was planned* (BCWS) and is represented by Equation (2.9):

$$V_S = \text{BCWP} - \text{BCWS} \qquad \text{Equation (2.9)}$$

A positive V_S (SPI >1.0) is desired because it means that the actual amount of work performed is greater than the amount of work scheduled and the project is therefore ahead of schedule.

SPI is calculated for the project as a cumulative value to reflect to-date schedule status. Although the project schedule rating shown in Table 2.2 can be applicable to some projects, it is proposed for illustration purposes only and needs to be modified for every project. Since construction projects are unique in nature, performance-rating tables must reflect the project specific conditions and the project controls philosophy.

Table 2. 2 Schedule Performance Rating Table

Condition	Rating	Index Range
A	Outstanding Performance	$I > 1.15$
B	Exceeds Target	$1.05<I<= 1.15$
C	Within Target	$0.95<I<= 1.05$
D	Below Target	$0.85<I<= 0.95$
F	Poor Performance	$I <= 0.85$

The SPI is further divided into the following schedule sub-indices as shown in level 3 of Figure 2.2. These sub-indices are calculated by dividing the earned value by the scheduled value. It should be noted that these sub-objectives are not fixed and need to be modified for each project.

- Engineering Schedule Performance Index (SPI_E)
- Procurement Schedule Performance Index (SPI_P)
- Construction Schedule Performance Index (SPI_C)

3- Billing Performance Index (BPI)

A critical factor for construction organizations to run a profitable business is their ability to carry out construction operations with minimal financing costs. The establishment of bank drafts is a common method of financing construction projects (Ahuja 1976). At any period during construction, contractors may not be able to execute any work if cash is not available despite the obligation to abide by the schedule. Most project managers recognize the need to control the cost and schedule, but fail to monitor the cash flow status and how it can affect the overall project success. Project managers must understand the impact of correct and timely invoicing on cash flow and ultimately on project profitability. Financing construction work is a critical management task and must be properly handled otherwise scheduled dates are not to be met. The interdependency between the billing performance index (BPI) and the schedule performance index (SPI) are very obvious. Unless Contractors secure adequate cash to keep construction work running as planned, the schedule will definitely be impacted. Elazouni and Gab-Allah (2004) presented an integer-programming finance-based scheduling method to produce financially feasible schedules that balance the financing requirements at any period with the cash available during that same period.

Many of the existing project management tools monitor cost, time, safety and quality without considering the impact of cash flow on the ultimate project success. Some other tools monitor cash flow at the beginning of the project for financing purposes and at the end for auditing purposes. This research suggests that cash flow management be used as part of the integrated control mechanism and be monitored by project management, along with performance attributes, on an on-going basis. Gardiner and Stewart (2000) proposed that investment appraisal techniques, such as the Net Present Value (NPV), should be used as an ongoing monitor of project health.

In lump sum projects, contractors are typically paid based on their demonstrated percentage complete, together with the approved revenue (as stipulated in the contract) for the completed work. This is simply equivalent to the Earned Revenue of Work

Performed (ERWP). In this context, the Billing Performance Index (BPI) measures the efficiency of invoicing the Client for the earned work. The BPI is determined by dividing the Billed Revenue by the Earned Revenue for the Work Performed. Submitting invoices to the client on time enhances the project cash flow and minimizes the cost of borrowed money. The assumption here is that the project is a lump sum contract and that billing is based on the physical progress earned. The BPI is given by Equation (2.10):

$$BPI = BRWP / ERWP \qquad \text{Equation (2.10)}$$

Where:

BRWP = Billed Revenue of Work Performed, or the cumulative amount of invoices, and

ERWP = Earned Revenue of Work Performed, or the revenue earned for the actual work accomplished to date.

An accurate measurement of the ERWP will enable contractors to invoice the client for all the actual work accomplished. This will decrease the financial risks in fixed-price or lump sum contracts.

A BPI value between 0.95 and 1.0 is desired because it means that the amount billed by the contractor covers all or most of the work earned and the project is therefore efficient in billing the client. Because the contractor cannot bill more than what is earned, the maximum value of BPI is 1.0. Based on Equation (2.10), the Billing Variance (V_B) is the difference between BRWP and ERWP.

BPI is calculated for the project as a cumulative value to reflect to date billing data. The project billing rating values shown in Table 2.3 are proposed for demonstration only and need to be customized for every project.

Table 2. 3 Billing Performance Rating and Normalization Table

Condition	Rating	Index Range	BPI Range
A	Outstanding Performance	I > 1.15	BPI > 0.98
B	Exceeds Target	1.05<I<= 1.15	0.95<BPI<= 0.98
C	Within Target	0.95<I<= 1.05	0.90<BPI<= 0.95
D	Below Target	0.85<I<= 0.95	0.85<BPI<= 0.90
F	Poor Performance	I <= 0.85	BPI <= 0.85

The BPI is further divided into the following billing performance indices as shown in level 3 of Figure 2.2 which are calculated by dividing the billed revenue value by the earned value. As every project is unique, this classification of sub-indices is proposed for demonstration only and need to be modified to reflect the specific scope of work.

- Building Works Billing Performance Index (BPI_B)
- Site Works Billing Performance Index (BPI_S)
- Off-site Fabrication Billing Performance Index (BPI_F)

Note that the comparison between what is billed to-date (BRWP) with what is incurred to-date, or the Budgeted Cost of Work Performed (BCWP), can provide an indication of the cash flow status of the project.

4- Profitability Performance Index (PPI)

The Profitability Performance Index (PPI) is a measure of how profitable the project is to date. The PPI is determined by dividing the Earned Revenue of the Work Performed (ERWP) by the Actual Cost of the Work Performed (ACWP). The actual cost should be inclusive of all direct, in-direct and overhead costs incurred to date. At the end of the project, the PPI is indicative of the overall project profit and the ERWP will be equal to the total final Contract Amount. The PPI is given by Equation (2.11):

PPI = ERWP/ ACWP Equation (2.11)

Where:

ERWP = Earned Revenue of Work Performed, or the revenue earned for the actual work accomplished to date.

ACWP = Actual Cost of Work Performed. It is the cost incurred to complete the accomplished work to-date.

A PPI value greater than 1.0 is desired because it means that the revenue earned by the contractor for the amount of work achieved to-date is greater than the cost incurred for that same work and the project is therefore profitable.

PPI is calculated for the project as a cumulative value to reflect to date profitability status. Project Profitability ranges from one company to another and even within the same company for different project types. The project profitability-rating scale shown in Table 2.4 is proposed for illustration purposes only:

Table 2. 4 Profitability Performance Rating and Normalization Table

Condition	Rating	Index Range	PPI Range
A	Outstanding Performance	I > 1.15	PPI > 1.3
B	Exceeds Target	1.05<I<= 1.15	1.2<PPI<= 1.3
C	Within Target	0.95<I<= 1.05	1.05<PPI<= 1.2
D	Below Target	0.85<I<= 0.95	0.90<PPI<= 1.05
F	Poor Performance	I <= 0.85	I <= 0.90

The calculated PPI (CI) value can be converted into the normalized PPI (NI) value using Figure 2.4, where NI = f (CI) and NI and CI are directly proportional.

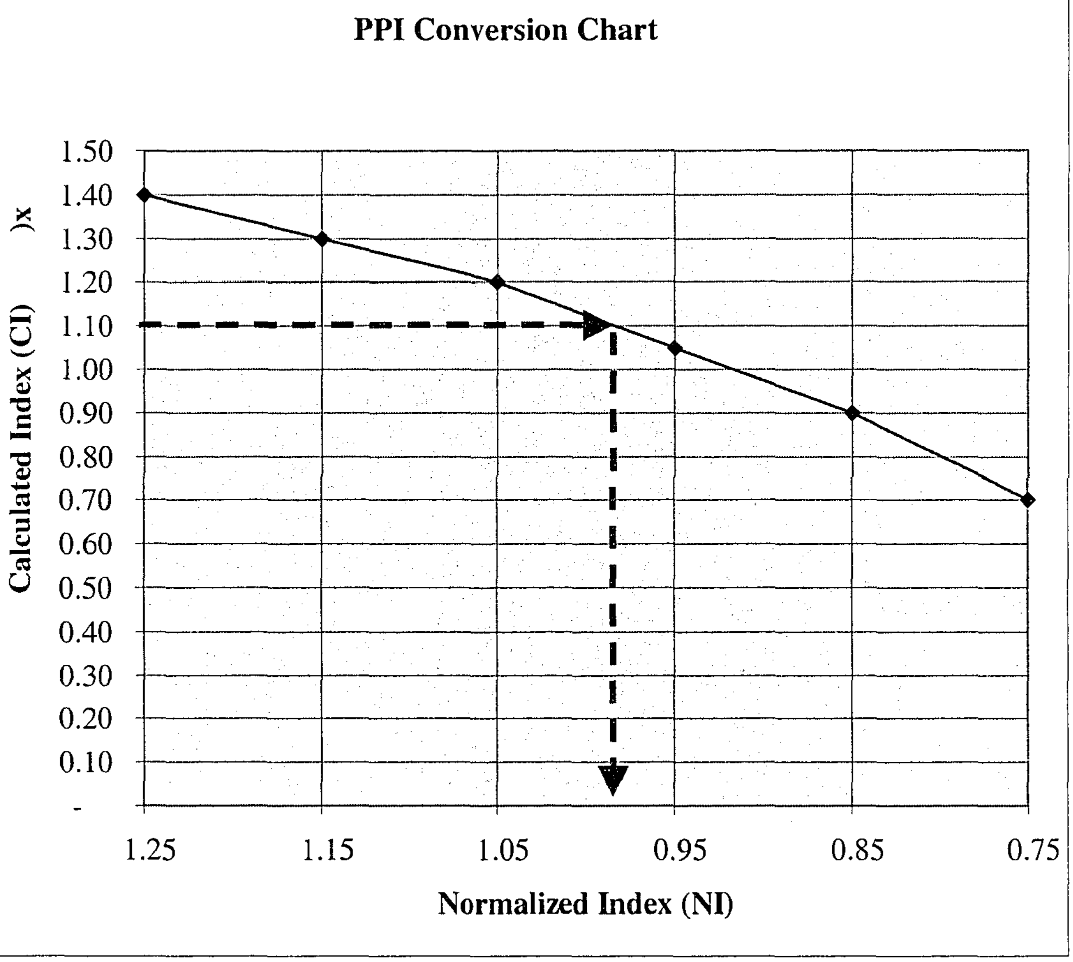


Figure 2. 4 Linear Transformation between Normalized and Calculated PPI Index

The PPI conversion chart shown in Figure 2.4 is proposed for demonstration purposes only. The objective of this study is to explain the methodology and every company must develop its own profitability targets and charts.

The PPI can be further divided into many profitability performance sub-indices as shown in level 3 of Figure 2.2. The following four sub-indices, proposed for demonstration only, are calculated by dividing the earned revenue value by the actual cost value.

- Civil Works Profitability Performance Index (PPI_V)
- Concrete Works Profitability Performance Index (PPI_C)

- Mechanical Works Profitability Performance Index (PPI_M)
- Electrical Works Profitability Performance Index (PPI_E)

5- Safety Performance Index (SFI)

A company's reputation for excellent safety performance is hard to establish and is extremely fragile. It is probably a contractor's greatest asset. The Safety Performance Index, as proposed in this model, is a measure of how safe the site activities are carried out without lost time incidents. Maintaining an excellent safety record is vital to the project success and is considered to be one of the most important project performance indices. In almost all projects, the contractor and owner's business objectives place a strong emphasis on construction safety. In order to maintain a good reputation within the construction industry and to properly care for the safety and well being of the project staff and labor force, it is obvious that safety be a top business objective in any company.

Every contractor must have an objective of *zero (0)* site accidents and procedures to eliminate any source of risk or danger to the workforce. Many construction organizations are promoting *zero harm* culture in all their projects. It should be noted that safety is a cooperative effort requiring the participation of every worker. A key element in achieving a zero-accident working environment is getting all staff and workers involved in the development of a safe worksite. Senior leadership involvement, proper planning, a good safety program, the right tools, safety training to increase awareness, and good housekeeping are some measures to prevent accidents. Near-miss accidents should never be ignored and preventive measures must be implemented to make sure it does not happen again. Companies with poor safety records are usually excluded from future bids. Attention and dedication to injury and incident free execution of work should be continuous through out the construction phase.

In this research, the calculation used to determine the safety performance of projects is based on an industry-wide formula. Accordingly, the non-normalized SFI is the Lost Time Incident (LTI) Frequency Rate given by:

$$SFI = \frac{LTI * C}{M} \qquad \text{Equation (2.12)}$$

Where:

LTI = Number of Lost Time Incidents to date

M = Total man-hours expended to date; and

C = is a constant (200,000) which represents 100 employees working for a full year (100 x 2,000).

SFI is calculated for the project as a cumulative value to reflect to-date safety status. Although every company should work towards the ultimate goal of *Zero Harm* and the elimination at source of any risks, a project safety rating scale is proposed in Table 2.5 for illustration only.

Table 2. 5 Safety Performance Rating and Normalization Table

Condition	Rating	Index Range	SFI Range
A	Outstanding Performance	I > 1.15	SFI = 0
B	Exceeds Target	1.15>=I> 1.05	0< SFI <= 0.1
C	Within Target	1.05>=I> 0.95	0.1 <SFI<= 0.3
D	Below Target	0.95>=I> 0.85	0.3<SFI<= 1.0
F	Poor Performance	I <= 0.85	SFI > 1.0

The safety rating scale shown in the above table is based on the author's experience with some industrial projects where the target was one LTI every One Million man-hours or a SFI of 0.2. These ranges might change from one company to another and is a function of the safety culture and the corporate strategic goals. Some projects might adopt different safety policies or more aggressive safety performance targets. Some projects may choose to measure, in addition to the frequency of lost time incidents, the severity of accidents as expressed by Equation (2.13):

$$\text{Severity} = \frac{\text{Number of Lost Time Days} \times 200{,}000}{\text{Man-hours Worked}} \qquad \text{Equation (2.13)}$$

Again, the purpose of this work is not to advocate certain safety norms but rather to introduce a tool that would allow the project teams to formalize the way they evaluate projects.

The calculated SFI (CI) value can be converted into the normalized SFI (NI) value using Figure 2.5 where NI = f (CI) and NI and CI are inversely proportional.

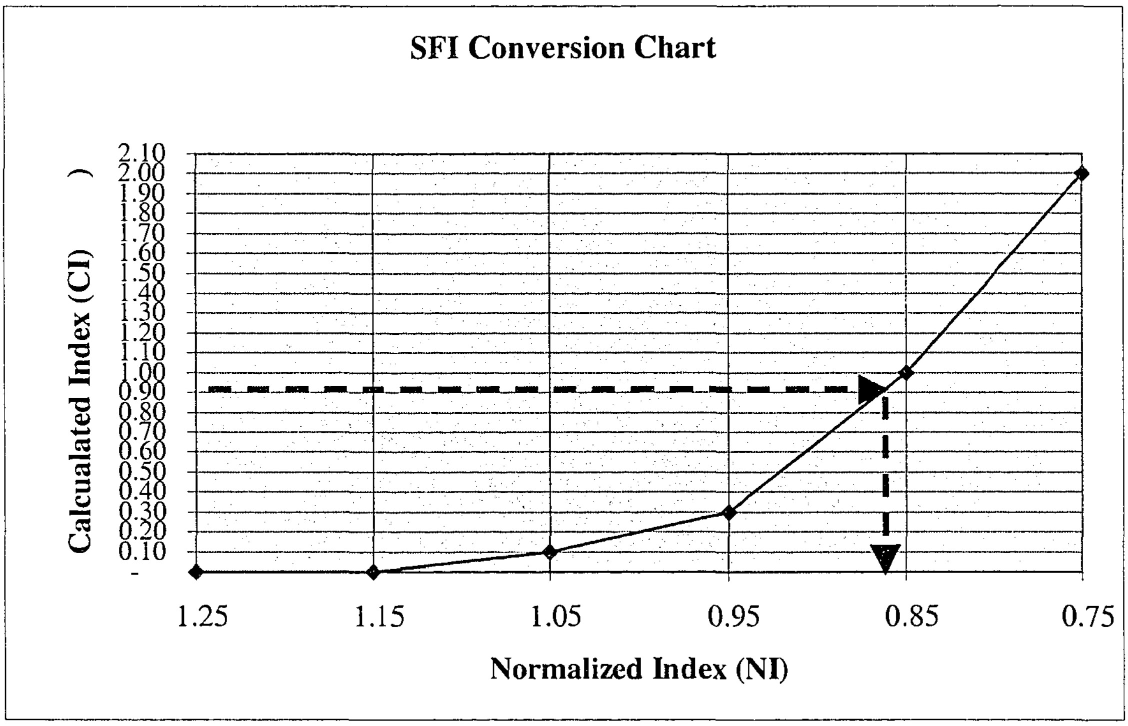


Figure 2. 5 Linear Transformation between Normalized and Calculated SFI Index

6- Quality Performance Index (QPI)

The demand for high quality projects is on the rise throughout the construction market. Quality is a major project performance attribute that requires measurement and continuous improvement. A strong quality performance can have the following benefits:

- Good quality can enhance an organization's ability to market its services and consequently can be a powerful marketing tool.
- Good quality increases the client satisfaction and increases the chances for repeat business.
- Good quality processes make the job easier, reduce the amount of rework, and improves the overall effectiveness and efficiency of construction operations.

The Quality Performance Index is a measure of consistency in the application of the Project Standards and Procedures as well as the compliance of the delivered product with the project specifications. Non-consistency in the application of project processes will lead to rework, poor quality audits and high number of Non Conformance Reports (NCR's). From the contractor's perspective, the QPI is best measured by the Construction Field Rework Index (CFRI), as defined in the pilot study for "Measuring and Classifying Construction Field Rework". The study was carried out by the University of Alberta and presented to the "Construction Owners Association of Alberta (COAA) Field Rework Committee" (Fayek et al. 2003). The study defined field rework as:

"Activities in the field that have to be done more than once in the field, or activities which remove work previously installed as part of the project regardless of source, where no change order has been issued and no change of scope has been identified by the owner".

The non-normalized QPI is given by:

QPI = CFRI = Construction Field Rework Index, where:

$$\text{CFRI} = \frac{\text{Total Direct and Indirect Cost of Rework performed in the Field}}{\text{Total Field Construction Phase Cost}} \quad \text{Equation (2.14)}$$

For further details, refer to the pilot study by Fayek et al. (2003).

QPI is calculated for the project as a cumulative value to reflect to date quality status. The following project quality ratings table is proposed for illustration purposes and need to be modified for every project.

Table 2. 6 Quality Performance Rating and Normalization Table

Condition	Rating	Index Range	QPI Range (%)
A	Outstanding Performance	I > 1.15	CFRI <= 0.5
B	Exceeds Target	1.15>=I> 1.05	0.5<CFRI<= 1
C	Within Target	1.05>=I> 0.95	1<CFRI<= 2
D	Below Target	0.95>=I> 0.85	2<CFRI<= 4
F	Poor Performance	I <= 0.85	CFRI > 4

For engineering projects, the Engineering Rework Index (ERI), the number of NCR's (Non-Conformance Reports), and number of Quality Audits can be introduced as additional parameters to measure the quality performance index.

The calculated QPI (CI) value can be converted into the normalized QPI (NI) value using Figure 2.6 where NI = f (CI) and NI and CI are inversely proportional.

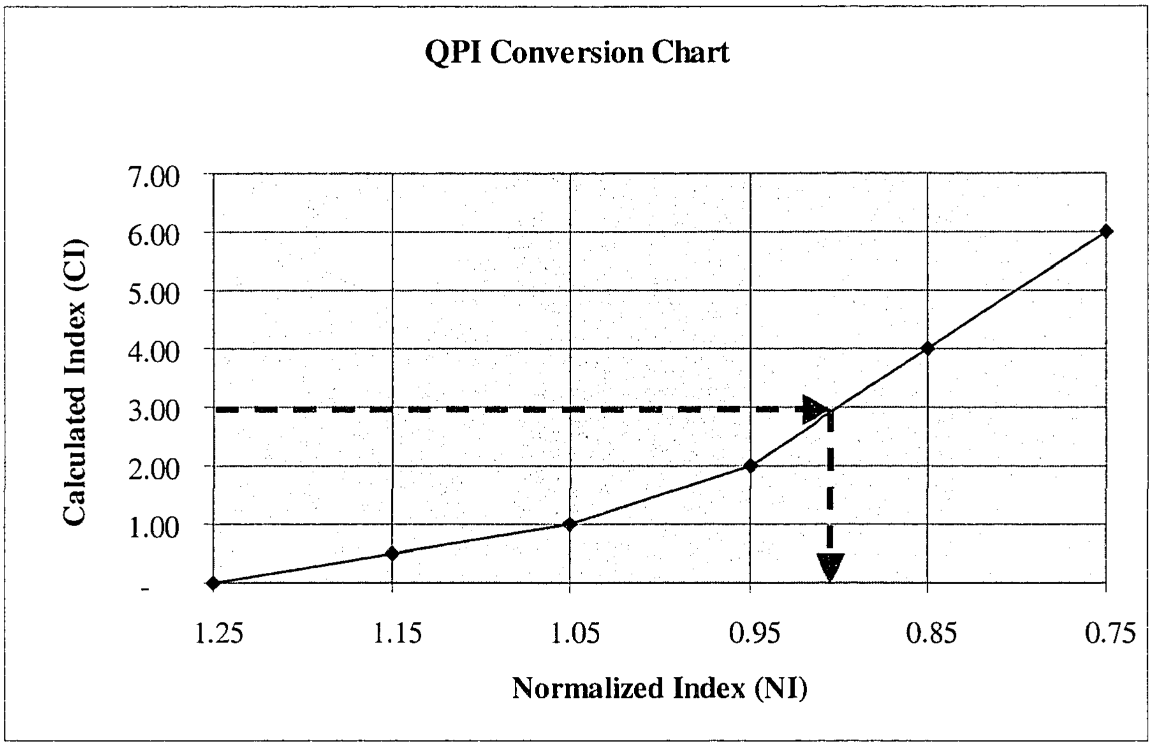


Figure 2. 6 Linear Transformation between Normalized and Calculated QPI Index

7- Team Satisfaction Index (TSI)

Human factors have a major impact on project quality and the successful completion of projects. The Project Team Satisfaction Index (TSI) is a measure of how satisfied the Project Team is. Building and sustaining high performing teams in today's dynamic construction environment is a challenging task. Team members should support each other and communicate openly and clearly. Research conducted by the Construction Industry Institute Planning Research Team (CII 1995) has established a clear link between teamwork and positive project performance. Thamhain (2004) identified the strong linkage between the project team environment and team performance. This field study concludes that organizations that satisfy personal and professional needs of team members seem to have the strongest effect on commitment and overall team performance. A professionally stimulating environment also decreases communication barriers, and increases the tolerance of conflict. Many studies indicate that project team motivation is one of the top factors contributing to project success. Mohsini and Davidson (1992) maintained that inter-organizational conflicts in a construction project would negatively impact its performance. Developing a team atmosphere on a project is necessary for the project to be successful because the team members will work together towards the objectives (Rowings et al. 1987). Parker and Skitmore (2005) found that project management turnover occurs predominantly during the execution phase of the project mainly due to career and personal development and dissatisfaction with the organizational culture. The same study confirmed that turnover negatively impacts the performance of the project team, and consequently the project. Based on above, it is of paramount importance to regularly monitor and evaluate the performance of the project team and deal with team functioning problems as it is directly related to project performance.

The TSI is determined by calculating the earned rating for every area of concern to the team member based on his/her evaluation and the priority assigned to every area of concern. The priority weights are measured using the AHP approach as will be explained later. This performance measure will help the project leader to address the problems within his team. This will lead to productivity improvement and consequently contribute to the overall project performance since the team morale will influence the efficiency and effectiveness of the project execution processes. Effective management of project human resources would result in gaining a competitive advantage and thus contributes to a project's success. The non-normalized TSI is given by:

$$TSI = \sum_{i=1}^{12} Wi * Ri$$

$$= W_1{*}R_1 + W_2{*}R_2 + W_3{*}R_3 + \ldots + W_{11}{*}R_{11} + W_{12}{*}R_{12} \qquad \text{Equation (2.15)}$$

Where:

W's = Relative weights for the various areas of concern. $\sum_{i=1}^{12} W_i = 1$.

And

R's = Ratings for the areas of concern on a scale from 1 to 10, 10 being the highest.

Based on discussions carried out by the author with team members in various construction projects, twelve areas of concern were identified and are listed in Table 2.7.

Table 2. 7 Team Members Satisfaction Rating Table

No	Team Member Area of Concern	Priority Wt.	Satisfaction from (1- 10)	Earned Rating
1	Involvement in the project	W_1	R_1	W_1*R_1
2	Client/suppliers response to TM needs	W_2	R_2	W_2*R_2
3	Project Manager response to TM needs	W_3	R_3	W_3*R_3
4	Adequacy of equipment to get the work done	W_4	R_4	W_4*R_4
5	Training received to carry out the job	W_5	R_5	W_5*R_5
6	Financial compensation	W_6	R_6	W_6*R_6
7	Clarity of project related responsibilities	W_7	R_7	W_7*R_7
8	Quality of supervision	W_8	R_8	W_8*R_8
9	Interest in nature of work	W_9	R_9	W_9*R_9
10	Coordination with the various disciplines	W_{10}	R_{10}	W_{10}*R_{10}
11	Execution of work as per Company procedure	W_{11}	R_{11}	W_{11}*R_{11}
12	Access to Project Baselines & progress report	W_{12}	R_{12}	W_{12}*R_{12}

Once the satisfaction value for each area of concern is calculated, the overall area satisfaction value can be determined by calculating the geometric mean of all the individual ratings. The priority weights (W_1,...,W_{12}) are determined by the AHP method as will be explained in section 2.6. To normalize the calculated index, a project team satisfaction-rating scale is proposed for illustration as shown in Table 2.8.

Table 2. 8 Team Satisfaction Performance Rating and Normalization Table

Condition	Rating	Index Range	TSI Range
A	Outstanding Performance	I > 1.15	TSI > 9.5
B	Exceeds Target	1.05<I<= 1.15	9.0 <TSI<= 9.5
C	Within Target	0.95<I<= 1.05	8.0 <TSI<= 9.0
D	Below Target	0.85<I<= 0.95	6.0 <TSI<= 8.0
F	Poor Performance	I <= 0.85	TSI<= 6.0

The calculated TSI (CI) value can be converted into the normalized TSI (NI) value using Figure 2.7 where NI = f (CI) and NI and CI are directly proportional.

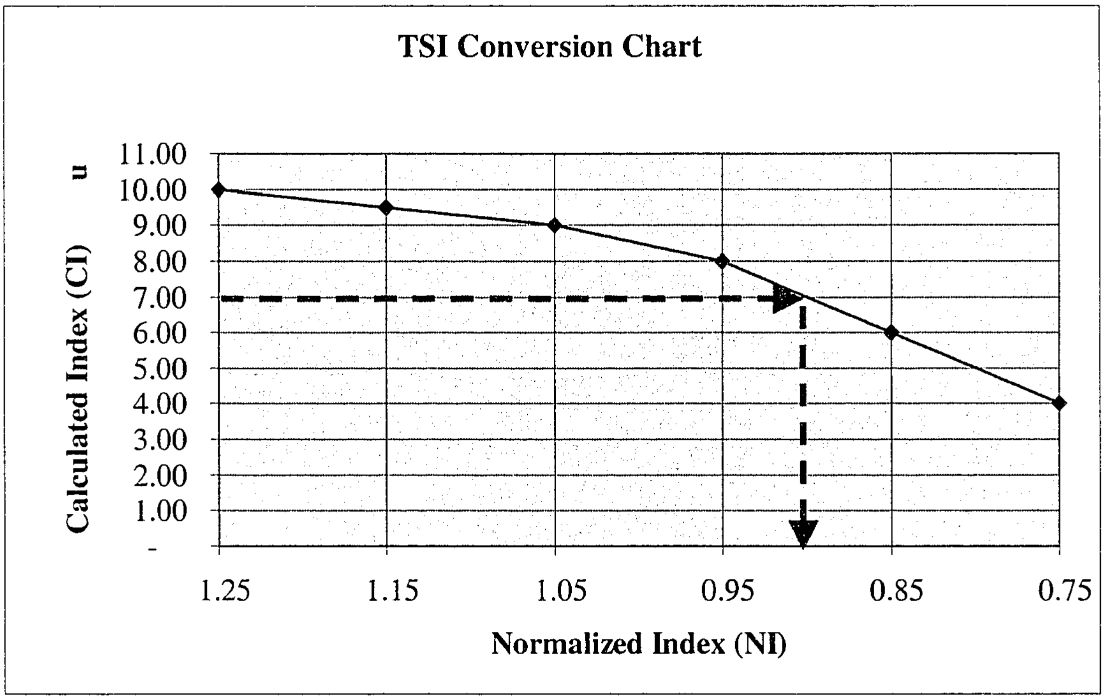


Figure 2. 7 Linear Transformation between Normalized and Calculated TSI Index

8- Client Satisfaction Index (CSI)

Meeting the expectations of the project owner (client) is the only way to ensure that a contracting company will continue to have repeat business. A formal survey or asking very basic questions could help us know better our clients. Because what gets measured gets done, it is important to measure the clients' expectations against an established baseline. Sims and Anderson (2003) suggested eight steps, including quantification of expectations, which a contracting organization can use to maintain an on going and working relationship with its clients.

Ideally, the owner's project objectives should be the basis on which the client satisfaction index is measured. In some cases, the client's objectives are formally communicated to the contractor. In other cases, they are verbally communicated, or implied in the contract documents, correspondence, and meetings (Rowings et al. 1987). In both cases, and to ensure that the client is satisfied with all the aspects of performance, the contractor's objectives should be closely aligned with the client's objectives (Rowings et al. 1987). Moreover, open lines of communication should be maintained both within and between the owner's firm and the construction firm.

It should be noted that the objectives of the Client are normally linked to the expected performance of the project upon its completion. On the other hand, the project management objectives are directly related to the actual management of the construction operations. This difference in views can cause completed projects to be both successful and disastrous at the same time. The concept of partnering will make all participants share to some degree in the success or failure of a project.

In this research, the Client Satisfaction Index evaluates the satisfaction of the Client's needs in a global sense. The CSI is determined by calculating the earned rating for every Client's area of concern based on the evaluation and the priority assigned by the Client to each area of concern. The areas of concern and their significance should be evaluated taking into consideration the client's specific objectives. The priority weights are measured using the AHP process as will be explained later. This performance measurement will help the Project Leader to get client feedback in a structured manner and address any area of concern the customer might have. The client should always have confidence in the capability of the Project Team/ Company to carry out the current job as well as future work and to meet their expectations. In today's competitive environment, ignoring the customer feedback may generate a downward spiral that could negatively affect the business of the contractor. TSI and CSI are interdependent in the sense that ignoring the needs of the project team members makes it very difficult to create a desire within the team to care for the needs of the external customer. The non-normalized CSI is given by:

$$CSI = \sum_{i=1}^{12} Wi * Ri$$

$$= W_1{*}R_1 + W_2{*}R_2 + W_3{*}R_3 + \dots\dots\dots\dots + W_{11}{*}R_{11} + W_{12}{*}R_{12} \qquad \text{Equation (2.16)}$$

Where:

W's = Relative weights for the twelve areas of concern. $\sum_{i=1}^{12} W_i = 1$

R's = Ratings for the areas of concern on a scale from 1 to 10, 10 being the highest.

Based on discussions carried out by the author with many client organizations and construction project owners during the past ten years, twelve areas of concern were identified and are listed in Table 2.9.

Table 2. 9 Client Satisfaction Rating Table

No	Client Area of Concern	Priority Wt.	Satisfaction from (1-10)	Earned Rating
1	Understanding of the project requirements	W_1	R_1	W_1*R_1
2	Understanding of Client system & procedures	W_2	R_2	W_2*R_2
3	Response to the Client requests and/or needs	W_3	R_3	W_3*R_3
4	Flexibility and adjustment to changes	W_4	R_4	W_4*R_4
5	Overall capability of contractor project team	W_5	R_5	W_5*R_5
6	Effective communication	W_6	R_6	W_6*R_6
7	Innovation in problem solving	W_7	R_7	W_7*R_7
8	Performance with respect to cost	W_8	R_8	W_8*R_8
9	Performance with respect to schedule	W_9	R_9	W_9*R_9
10	Performance with respect to service quality	W_{10}	R_{10}	W_{10}*R_{10}
11	Performance with respect to product quality	W_{11}	R_{11}	W_{11}*R_{11}
12	Performance with respect to safety procedures	W_{12}	R_{12}	W_{12}*R_{12}

Once a formal Client Satisfaction Survey is completed, the Contractor should use it to propose mitigation actions if required. This feedback will help the construction company to continuously improve its work processes and services to its customers thus enabling the company to gain competitive edge over other contractors. Most often, informal "face to face" surveys of client satisfaction conducted by the Contractor's representative would not disclose the real situation and the client's answers tend to be diplomatic.

To normalize the obtained index, a client satisfaction rating scale is proposed in Table 2.10. The proposed scale is for illustration only and needs to be modified to reflect the project specific conditions.

Table 2. 10 Client Satisfaction Rating and Normalization Table

Condition	Rating	Index Range	CSI Range
A	Outstanding Performance	I > 1.15	R > 9.5
B	Exceeds Target	1.05<I<= 1.15	9.0 <R<= 9.5
C	Within Target	0.95<I<= 1.05	8.0 <R<= 9.0
D	Below Target	0.85<I<= 0.95	6.0 <R<= 8.0
F	Poor Performance	I <= 0.85	R<= 6.0

The calculated PPI (CI) value can be converted into the normalized PPI (NI) value using Figure 2.8 where NI = f (CI) and NI and CI are directly proportional.

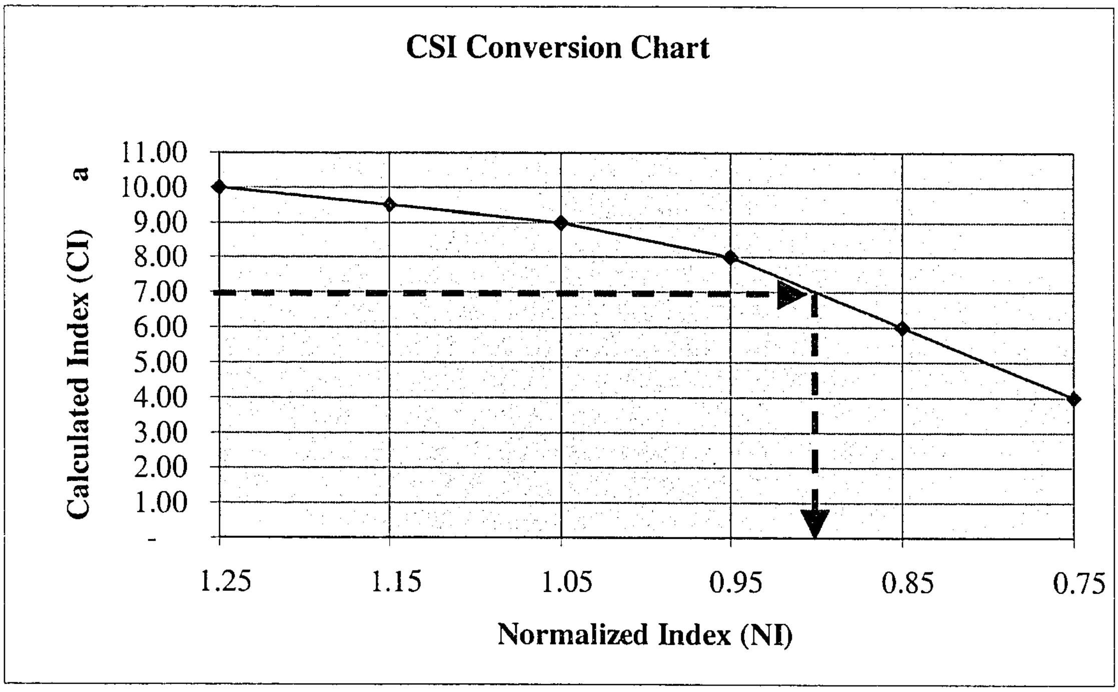


Figure 2. 8 Linear Transformation between Normalized and Calculated CSI Index

Secondary Performance Indices

There are some secondary performance indices that could be of some significance for some contractors; like measuring level of risk, contingency depletion, and time performance. The Time Performance Index (TPI) is measured by dividing the Scheduled Time of Work Performed (STWP) by the Actual Time of Work Performed (ATWP). Time variances are measured in time, whereas cost and schedule variances are measured in dollars as demonstrated above. A negative time variance indicates a delay and is thus unfavorable. Time Variance (V_T) is defined as the number of days between the scheduled time and actual time to perform the work to date and is represented by Equation (2.17).

$$V_T = \text{STWP} - \text{ATWP} \qquad \text{Equation (2.17)}$$

These secondary performance indices overlap with the above proposed eight indices. As shown above, the Time Performance Index (TPI) overlaps with the Schedule Performance Index (SPI), and contingency depletion is covered under the Cost Performance Index (CPI). As a result, they are not considered as independent variables in the project performance index equation. However, some companies may choose to consider these secondary indices.

2.5.3 Project Performance Index (PI)

Controlling all of the above performance attributes defines the need for a multi-dimensional Integrated Project Performance Management system (IPPM). To develop a useful index of project performance from the above results, a common measurement platform was established to normalize all the indices. Moreover, the classification of the performance variables into a common value scale made it possible to combine all eight indices into a project index (PI) equation. Combining the variables identified with the corresponding weights yields a weighted equation for the total project performance. This is only true if the condition of additive utility independence is satisfied as will be explained in the next section.

Mutual Preferential Independence

In the multi-attribute performance problem, the evaluation of project performance involves more than just one index. As a matter of fact, the proposed methodology has eight conflicting objectives to consider for every project. In order to deal with such a problem by means of the decision analysis approach, it is necessary to develop a multi-attribute utility function. There are no easy guidelines currently available for assessing such a function (Bunn 1982). In our case, however, the condition of *mutual preferential independence* can be satisfied in order to decompose the joint utility function into a summation of individual single attribute utility functions where utilities are values. In other words we can express the project performance index (*PI*) as a function F of the eight performance indices (*CPI, SPI, BPI, PPI, SFI, QPI, TSI, CSI*) as shown in Equation (2.18).

$$PI = F(CPI,...,CSI) = \sum_{i=1}^{8} w_i I_i \qquad \text{Equation (2.18)}$$

Where w_i = the value for the weights of the eight indices.

The above linear form holds because the mutual preferential independence of the eight performance indices is a sufficient condition for the additive decomposition of the joint project performance value function as shown in Equation 2.18 as opposed to a joint *utility* function (Bunn 1982).

An attribute A is said to be preferentially independent of B, if preferences for specific values of A do not depend upon B. For example, if we prefer, in a certain project, a Schedule Performance Index (SPI) of 1.0 regardless of the value of the Cost Performance Index (CPI), then SPI is preferentially independent of CPI. If CPI is also preferentially independent of SPI, then we refer to SPI and CPI as being mutually preferentially independent. Let us consider another example, if we prefer a safety performance of zero accidents (SFI) regardless of the values of the {CPI, SPI, PPI}, then SFI is preferentially independent of {CPI, SPI, PPI}. If {CPI, SPI, PPI} are also preferentially independent of

SFI, then we refer to SFI and {CPI, SPI, PPI} as being mutually preferentially independent. Mutual preferential independence has been found to hold in most cases of project performance trade-off situations. The Profitability Performance Index (PPI) and the Cost Performance Index (CPI) is one exception in this regard. The value of PPI, say "above target", may affect the project manager's preference for an "above target" or "exceptional" CPI value. PPI would not, therefore, be preferentially independent of CPI. Profitability has a separate performance index simply because some projects can end up profitable but behind budget. In addition, senior management is interested in the forecasted profit for financial planning purposes as much as the project manager is keen about meeting his budget.

Overall Performance Equation

Based on above and after proving that the condition of additive utility value independence of attributes holds, (PI) can be expressed in a linear additive form as:

$$PI = w_1 *CPI+ w_2*SPI+ w_3*BPI+ w_4*PPI + w_5*SFI+ w_6*QPI+w_7*TSI+ w_8*CSI \qquad \text{Equation (2.19)}$$

Where $\sum_{i=1}^{8} w_i = 1$ and

CPI, SPI, BPI, PPI, SFI, QPI, TSI, and CSI are the normalized performance indices as defined in the above section. $W_1...W8$ are the respective priority weights or relative importance of each index with respect to the overall project performance (PI). It should be noted that the priorities might vary with time because of changes in project scope, or simply due to human nature. For example, towards the end of the project the schedule priority may increase and that of cost will probably decrease. But at any time the summation of the weights is unity.

The eight performance indices are quantified and normalized as per the previously mentioned procedures. The analytical hierarchy process (AHP) is then used to derive the priority weights (*W's*) or relative importance of the indices using the eigen-value and eigen-vector of the pair-wise comparisons matrix as will be explained in the next section.

These weights will indicate how sensitive the outcome, or the overall performance (PI), to the performance indices and consequently to the various types of corrective actions.

Measurement of the project performance indices should take place at regular intervals, certainly monthly, but recommended to be weekly especially for short term or fast track projects. This is true for all indices except for the Team Satisfaction Index (TSI) and the Client Satisfaction Index (CSI) where measurement is not practical every week and can be assessed on a quarterly basis or whenever the project management team feels the necessity. These eight indices provide a wealth of data reflecting the true health of projects and assist the project management team to monitor, analyze, and initiate preventive measures if required.

2.6 Analytical Hierarchy Process (AHP) Methodology to derive priority weights

The second purpose of this research is to establish a model for evaluating the priority weights for the performance indices of a construction project through the application of the Analytical Hierarchy Process (AHP). AHP, a multi-criteria decision method developed by Saaty (Saaty 1982), is an appropriate tool because it provides the ability to incorporate both qualitative and quantitative factors in the decision making process. AHP has been applied to solve unstructured problems in a variety of fields, ranging from engineering applications to research planning and political conflicts (Saaty 1982).

2.6.1 Role of AHP

The goal of the AHP in this research is to come up with a relative importance vector for the selected project performance attributes, (cost, schedule, billing, profitability, safety, quality, team satisfaction, and client satisfaction) based on knowledge and judgment of experts in the industry. The same methodology can be used to weight the attributes for the team and client satisfaction indices that reflect the perception and judgments of the project management team.

2.6.2 AHP applications

AHP is applied to planning, conflict resolution, benefit/cost analysis, and resource allocation (Saaty 1982). AHP applications in the domain of manufacturing, construction engineering and management have proved to be effective. However, applications of AHP still need human judgment and this relies on the experienced end users. AHP was used to analyze the output from the FMS (flexible manufacturing systems) simulation models (Chan et al. 2000). The AHP was also used to establish a model for evaluating the communication resistance among the team members of a construction project (Cheng et al. 2003). A model using (AHP) was developed to select the most appropriate project delivery method (Al Khalil 2002). Cagno et al. (2001) used a simulation approach based on AHP to assess the probability of winning in a competitive bidding process where competing bids are evaluated on a multiple criteria basis from a contracting point of view. The analytical hierarchy process (AHP) has been used to determine the relative importance weights for a set of design performance criteria to optimize the building design by selecting the appropriate building assemblies (Nassar et al. 2003). Hastak (1998) proposed a decision support system called AUTOCOP that utilizes AHP to analyze the tangible and the intangible set of criteria involved in the evaluation of advanced automation or conventional construction processes. In a study carried out by Cheung et al. (2002), AHP was used to prioritize the alternative dispute resolution (ADR) process attributes in construction projects. Chua et al. (1999) used AHP to weigh the relative importance of the success factors to identify the most critical among them. The work by Dozzi et al. (1996) and Pocock et al. (1996) adopted the AHP method to determine the relative weights of the criteria in a fuzzy-logic system for the selection of design/build proposals. Chao and Skibniewski (1995) presented a neural network (NN) based approach that used the AHP method to generate the input parameters of a neural network model. Skibniewski and Chao (1992) used AHP for the evaluation of advanced construction technology. A multi-criteria systematic approach based on the analytical hierarchy process (AHP) was developed by El Mikawi and Mosallam (1996) to assist decision makers in evaluating the use of advanced materials. Stewart and Horowitz (1991) presented an approach based on AHP for measuring environmental impacts of projects. AHP was used to construct departmental locations within a facility (Partovi and Burton 1992). Dey et al. (1996) used AHP to carry out risk analysis due to the subjective nature of risks in construction projects.

2.7 Model development

AHP method is used to breakdown the project performance system into its basic components or performance factors; arranging them in a hierarchical order; assigning numerical values to subjective judgments on the relative significance of each performance factor; and synthesizing the judgments to derive the priority weights of the factors. The AHP is also used to provide an effective structure for project team decision-making by imposing a discipline on the team's judgment process thus leading to consistent decisions and results.

2.7.1 Project Performance Hierarchical Structure

The project performance system is best understood by breaking it down into basic performance areas and by structuring the attributes hierarchically according to their essential relationships. Every index in one level is related to an index in the next higher level, which serves as a criterion for evaluating the relative importance of the indices in the level below. The design of the AHP hierarchy utilizes the project performance hierarchy outlined in Figure 2.3. The proposed hierarchical model consists of three levels and will be used in the case study. At the top level of the hierarchy is the ultimate goal or project performance index. The second level consists of eight performance indices that constitute the attributes of project performance, namely: cost, schedule, billing, profitability, safety, quality, team and client satisfaction. At the third level of the hierarchy are the sub-indices under each of the eight project performance indices. Hierarchies are flexible and can be modified to reflect the performance criteria of a specific project. The following is the proposed performance indices and sub-indices:

Cost Performance Index (CPI):

- Indirect Cost Performance Index

- Engineering Cost Performance Index
- Labor Cost Performance Index
- Material Cost Performance Index
- Construction Equipment Cost Performance Index
- Subcontractor Cost Performance Index
- Tools/consumables Cost Performance Index

Schedule Performance Index (SPI):

- Engineering Schedule Performance Index
- Procurement Schedule Performance Index
- Construction Schedule Performance Index

Billing Performance Index (BPI):

- Building Works Billing Performance Index
- Site Works Billing Performance Index
- Off-site Fabrication Billing Performance Index

Profitability Performance Index (PPI):

- Civil Works Profitability Performance Index
- Concrete Works Profitability Performance Index
- Mechanical Works Profitability Performance Index
- Electrical Works Profitability Performance Index

Safety Performance Index (SFI):

- Lost Time Incident (LTI) Frequency Rate

Quality Performance Index (QPI):

- Construction Field Rework Index (CFRI)

Team Satisfaction Index (TSI):

- Involvement in the project
- Client/suppliers response to TM needs
- Project Manager response to TM needs
- Adequacy of equipment to get the work done
- Training received to carry out the job
- Financial compensation
- Clarity of project related responsibilities
- Quality of supervision
- Interest in nature of work
- Coordination with the various disciplines
- Execution of work as per Company procedure
- Access to Project Baselines & progress report

Client Satisfaction Index (CSI):

- Understanding of the project requirements
- Understanding of Client system & procedures
- Response to the Client requests and/or needs
- Flexibility and adjustment to changes
- Overall capability of contractor project team
- Effective communication
- Innovation in problem solving
- Performance with respect to cost
- Performance with respect to schedule
- Performance with respect to service quality
- Performance with respect to product quality
- Performance with respect to safety procedures

All the above sub-attributes are quantifiable as explained previously except for the attributes of the project team and client satisfaction indices where subjective judgments are needed. The AHP approach is used to assign priority weights to these sub-attributes with respect to their attributes.

2.7.2 Project Performance: A Linear Additive Utility Model

A multi-attribute utility function is comprised of the functions for the individual attributes and the weights that reflect the relative importance of these attributes. It was previously demonstrated the condition of additive utility independence of attributes holds and the project performance function can be represented as a *linear additive multi-attribute utility function*. In our case, the overall project performance index (PI) consists of the functions of the eight individual performance indices and their priority weights as shown in section 2.5. Since the various indices considered in evaluating the performance of projects (such as cost, schedule, billing, profitability, safety, quality, team and client satisfaction) are mutually preferentially independent as explained earlier, (PI) can be formulated as a *linear additive utility model.* This model is composed of two components: the individual performance functions and the priority weights. The functions were explained and formulated in section 3 and the weights will be assessed using the AHP methodology.

Based on above, the project performance index (PI), as a function of time, can be expressed as:

$$PI(t) = \sum_{i=1}^{8} W_i(t) * I_i(t) \qquad \text{Equation (2.20)}$$

Where:

$W_i(t)$ = Utility weight or the relative importance of the performance index *(I_i)* with respect to the overall project performance *(PI)* at time *t* of the project.

If the project team is fully aware of the project scope, objectives, and values; these weights should not change but stay constant throughout the project duration. Unfortunately; project priorities as viewed by management change with time, scope of work is usually dynamic, and human nature is not constant. For these reasons, the weights are not constant and usually vary as a function of time. For example, the relative weight of the Schedule Performance Index (SPI) of a project with high liquidated damages tends to increase towards the end of the project due to the increasing need to complete the project on time to avoid the high penalties. Also, the significance of safety to the project team usually increases after the first lost time incident (LTI) takes place.

It should be noted that:

$\sum_{i=1}^{8} W_i = 1$ At any time t of the project, and

$I_i(t)$ = Normalized performance index at time t of the project.

2.7.3 AHP process to derive utility weights and advantages

The AHP method is a powerful process for tackling unstructured, distributed project performance problems. The AHP incorporates judgments and values of the project management team in a logical manner. It depends on logic, knowledge, and experience to provide judgments. Through a mathematical sequence, using linear algebra and the matrix theory, the AHP synthesizes the judgments into a set of relative priorities. The priorities derived by AHP are used to quantify the team and client satisfaction indices and the overall project performance index (PI). The overall process is shown in Figure 2.9.

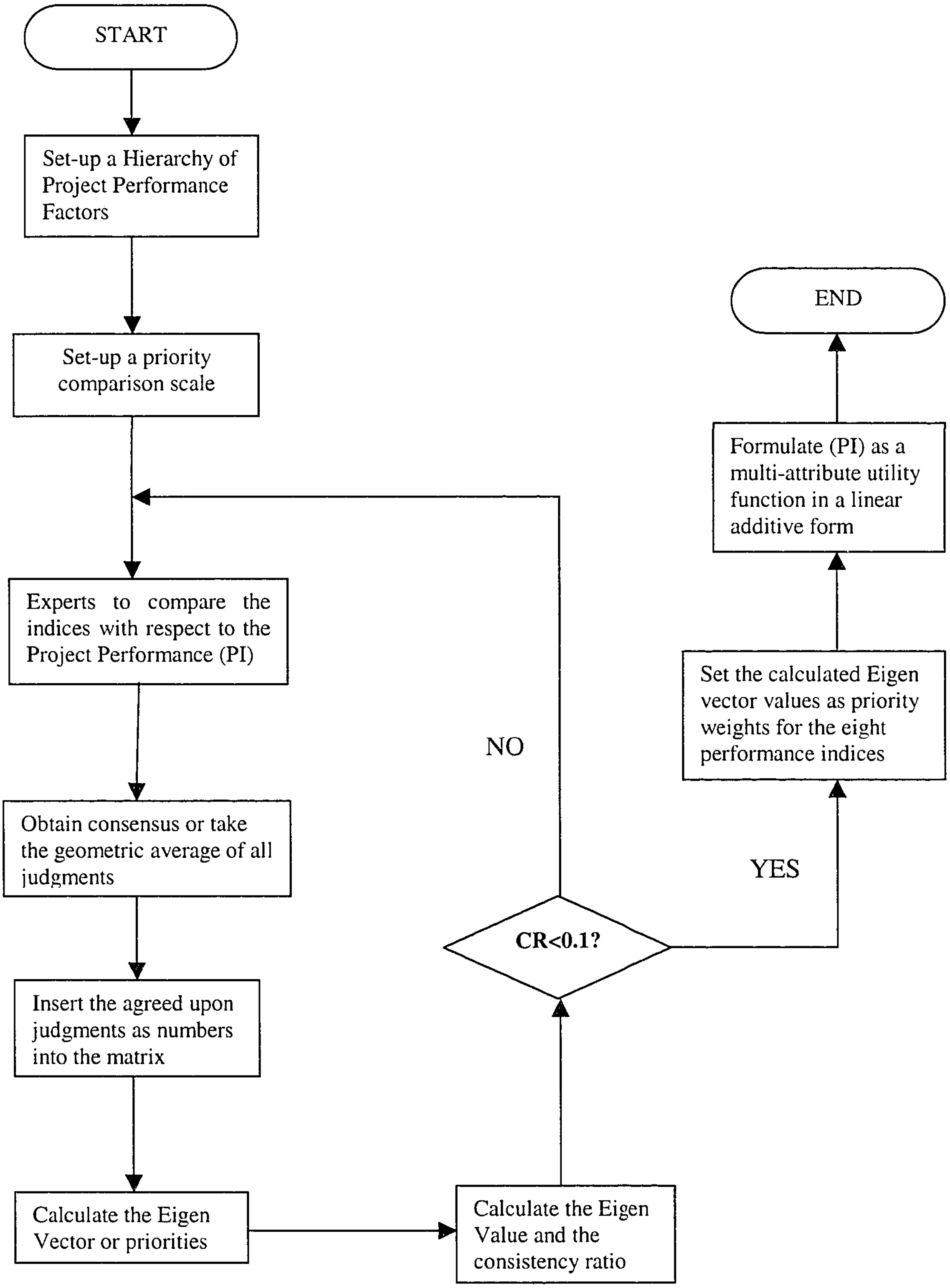


Figure 2. 9 Flow Chart for the AHP to derive priority weights for the indices

Advantages of AHP

The application of AHP to handle the problem of prioritization of indices has many advantages (Saaty 1982) and can be summarized as follows:

- **Measurement**: The AHP provides a scale for measuring qualitative factors and a method for establishing priorities within unstructured problems.
- **Hierarchic Structuring**: The AHP uses hierarchies to model problems that are identical to the project performance evaluation hierarchy.
- **Consistency:** The AHP assesses the logical consistency of judgments used in determining the priorities of the performance indices.
- **Interdependence:** The AHP can deal with the interdependence among the performance indices and does not insist on linear thinking.
- **Judgment and Consensus:** The AHP does not insist on consensus but synthesizes a representative outcome from diverse judgments.

Setting Priorities

The first step in establishing the priorities of the performance indices is to conduct pair-wise comparisons, that is, to compare the performance indices in pairs at one level with respect to the index at the level above. The pair-wise comparisons among the eight performance indices in level 2 of Figure 2.2 with respect to Project Performance Index (PI) at level one can be arranged in a matrix format [*A*] as shown in Table 2.11.

Table 2. 11 Pair-wise Comparison Matrix

$$[A] = \begin{array}{c|cccccccc|} \textbf{PI} & CPI & SPI & BPI & PPI & SFI & QPI & TSI & CSI \\ CPI & a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} \\ SPI & a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} & a_{27} & a_{28} \\ BPI & a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & a_{37} & a_{38} \\ PPI & a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} & a_{47} & a_{48} \\ SFI & a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} & a_{57} & a_{58} \\ QPI & a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} & a_{67} & a_{68} \\ TSI & a_{71} & a_{72} & a_{73} & a_{74} & a_{75} & a_{76} & a_{77} & a_{78} \\ CSI & a_{81} & a_{82} & a_{83} & a_{84} & a_{85} & a_{86} & a_{87} & a_{88} \end{array}$$

The above judgment matrix A is a positive, reciprocal, and square matrix since:

$$a_{ij} > 0 \qquad i,j = 1,\ldots\ldots,8$$

Since if CPI is 5 times more important than SPI with respect to PI then SPI is one fifth as important as CPI and thus we can write:

$$a_{ji} = 1/a_{ij} \qquad i,j = 1,\ldots\ldots,8$$

When comparing one performance index in a matrix with itself; for example, CPI with CPI, the result is unity hence we can write $a_{ii} = 1$. Then the judgment matrix can be represented as:

Table 2. 12 Judgment Matrix with respect to Project Performance

$$[A] = \begin{array}{c|cccccccc|} PI & CPI & SPI & BPI & PPI & SFI & QPI & TSI & CSI \\ \hline CPI & 1 & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} \\ SPI & 1/a_{12} & 1 & a_{23} & a_{24} & a_{25} & a_{26} & a_{27} & a_{28} \\ BPI & 1/a_{13} & 1/a_{23} & 1 & a_{34} & a_{35} & a_{36} & a_{37} & a_{38} \\ PPI & 1/a_{14} & 1/a_{24} & 1/a_{34} & 1 & a_{45} & a_{46} & a_{47} & a_{48} \\ SFI & 1/a_{15} & 1/a_{25} & 1/a_{35} & 1/a_{45} & 1 & a_{56} & a_{57} & a_{58} \\ QPI & 1/a_{16} & 1/a_{26} & 1/a_{36} & 1/a_{46} & 1/a_{56} & 1 & a_{67} & a_{68} \\ TSI & 1/a_{17} & 1/a_{27} & 1/a_{37} & 1/a_{47} & 1/a_{57} & 1/a_{67} & 1 & a_{78} \\ CSI & 1/a_{18} & 1/a_{28} & 1/a_{38} & 1/a_{48} & 1/a_{58} & 1/a_{68} & 1/a_{78} & 1 \end{array}$$

In the matrix shown in Table 2.12, the index *CPI* is compared to the indices *CPI, SPI, BPI, PPI, SFI, QPI, TSI, and CSI* in the first row with respect to the criterion *PI* in the upper left hand corner. This process is repeated for the other indices in the same manner. To complete the judgment matrix, the experts need, based on their experience and knowledge of the project, to fill the matrix based on the importance scale proposed in Table 2.13 by answering the following question: "How much more important is *Index 1* than *Index 2* with respect to the overall project performance? "

Table 2. 13 Intensity of Importance Scale

Scale	Definition	Explanation
1	Equal Importance	Two indices contribute **equally** to the Project Performance
3	Weak importance of one over another	Index 1 is **slightly favored** over Index 2
5	Medium Importance of one over another	Index 1 is **medium favored** over Index 2
7	Strong Importance of one over another	Index 1 is **strongly favored** over Index 2
9	Absolute Importance of one over another	Index 1 is **absolutely favored** over Index 2
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

The relative importance of one index over another with respect to the overall project performance index is represented by a numeric value. Table 2.13 is suggested based on Saaty's scale for pair-wise comparisons (Saaty 1982). It contains nine values that can be assigned to judgments when comparing pair of indices in each level of the hierarchy against the index in the next higher level.

Based on above, the pair-wise comparisons between the eight performance indices are represented by a matrix W as shown in Table 2.14. This pair-wise comparison matrix shown has no zeros, and consequently is considered an irreducible positive matrix having a unique Eigen vector solution corresponding to the maximum Eigen value (Saaty 1990).

Table 2. 14 Pair-wise comparison matrix

$$[W]= \begin{array}{cc} \boldsymbol{PI} & \begin{array}{cccccccc} CPI & SPI & BPI & PPI & SFI & QPI & TSI & CSI \end{array} \\ \begin{array}{c} CPI \\ SPI \\ BPI \\ PPI \\ SFI \\ QPI \\ TSI \\ CSI \end{array} & \begin{bmatrix} w_1/w_1 & w_1/w_1 & .... & ... & ... & ... & ... & w_1/w_8 \\ w_2/w_1 & w_2/w_2 & ... & ... & ... & ... & ... & w_2/w_8 \\ ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... \\ ... & ... & ... & ... & ... & ... & ... & ... \\ w_8/w_1 & w_8/w_2 & ... & ... & ... & ... & ... & w_8/w_8 \end{bmatrix} \end{array}$$

To populate the pair-wise comparison matrix, experts or the project management personnel need to compare the performance indices in pairs. The judgments applied should be based on logical thinking and experience and should take into account the project specific conditions. It should be emphasized that this technique does not under estimate the judgment of the project team but tries to present it in a consistent way.

Synthesizing the Judgments

The judgment matrix should be synthesized to get an estimate for the relative weights of the performance indices with respect to overall performance index (PI). To do so we have to solve the system: $Aw = nw$, *or* $(A - nI)\,w = 0$ in the unknown w, where $w = (w_1, \ldots\ldots, w_n)$ and matrix A is consistent and satisfies the "cardinal" consistency property $a_{ij}a_{jk} = a_{ik}$. This has a non-zero solution, if and only if, n is an Eigen value of A, or $\lambda_{\max} = n$ (Saaty 1990).

Knowing that the management team members cannot maintain perfect consistency in judgments, the judgment matrix **W** is not perfectly consistent and the problem of $Aw = nw$ becomes $Ww = \lambda_{\max}\, w$.

Note that for $\mathbf{A} = (a_{ij})$, and $\mathbf{W} = (w_i/w_j)$, we can write:

$$(A - W)\,w = (\lambda_{\max} - n)w \qquad \text{Equation (2.21)}$$

Which shows that the approximation to (a_{ij}) by (w_i/w_j) is the better the closer is $\lambda_{\max}$ to n. Solving $Ww = \lambda_{\max}\, w$ gives the following priority vector:

$$\mathbf{w} = [w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8] \qquad \text{Equation (2.22)}$$

Equation (2.22) is the Eigen vector corresponding to the maximum Eigen value of matrix **A.** The mathematics underlying the AHP technique to generate the relative importance weights for the project performance attributes/indices are based on linear algebra. The set of weights is shown in Table 2.15. The reader is referred to Saaty (1990) for the mathematical details.

Table 2. 15 Table of Relative weights or priorities for the performance indices

Index	Performance Index	Eigen Vector
I_1	CPI	w_1
I_2	SPI	w_2
I_3	BPI	w_3
I_4	PPI	w_4
I_5	SFI	w_5
I_6	QPI	w_6
I_7	TSI	w_7
I_8	CSI	w_8
	Total	**1.0**

The Eigen vector represents the priority weights or relative significance of the performance indices with respect to the overall project performance (PI).

$$PI = \sum_{i=1}^{8} w_i I_i \qquad \text{Equation (2.23)}$$

Where,

$$\sum_{i=1}^{8} w_i = 1$$

If we apply the same process to the factors impacting the team satisfaction, then we arrive at the priority vector for the Team Satisfaction Index (TSI) as shown in Table 2.16.

Table 2. 16 Table of Relative weights or priorities for the project team areas of concern

Index	Project team area of concern	Eigen Vector
I_1	Involvement in the project	v_1
I_2	Client/suppliers response to TM needs	v_2
I_3	Project Manager response to TM needs	v_3
I_4	Adequacy of equipment to get the work done	v_4
I_5	Training received to carry out the job	v_5
I_6	Financial compensation	v_6
I_7	Clarity of project related responsibilities	v_7
I_8	Quality of supervision	v_8
I_9	Interest in nature of work	v_9
I_{10}	Coordination with the various disciplines	v_{10}
I_{11}	Execution of work as per Company procedure	v_{11}
I_{12}	Access to Project Baselines & progress report	v_{12}

In this case, the Eigen vector represents the priority weights or relative significance of the areas of concern or attributes with respect to the project team satisfaction index (TSI). TSI is calculated using the following formula:

$$TSI = \sum_{i=1}^{12} v_i R_i \qquad \text{Equation (2.24)}$$

Where,

$$\sum_{i=1}^{12} v_i = 1$$

R_i is the rating on a scale of (1-10) for every aspect of team performance. In the same manner, we obtain the following priority weights for the client satisfaction index (CSI).

Table 2. 17 Table of Relative weights or priorities for the Client's areas of concern

Index	Client Area of Concern	Eigen Vector
I_1	Understanding of the project requirements	u_1
I_2	Understanding of Client system & procedures	u_2
I_3	Response to the Client requests and/or needs	u_3
I_4	Flexibility and adjustment to changes	u_4
I_5	Overall capability of contractor project team	u_5
I_6	Effective communication	u_6
I_7	Innovation in problem solving	u_7
I_8	Performance with respect to cost	u_8
I_9	Performance with respect to schedule	u_9
I_{10}	Performance with respect to service quality	u_{10}
I_{11}	Performance with respect to product quality	u_{11}
I_{12}	Performance with respect to safety procedures	u_{12}

The Eigen vector represents the priority weights or relative significance of the areas of concern or attributes with respect to the Client Satisfaction Index (CSI). CSI is calculated using the following formula:

$$CSI = \sum_{i=1}^{12} u_i R_i \qquad \text{Equation (2.25)}$$

Where,

$$\sum_{i=1}^{12} u_i = 1$$

Logical Consistency

Decisions should not be based on judgments that have low consistency. On the other hand, perfect consistency is very hard to maintain. A certain degree of consistency in judgments is necessary to get valid results in the real world of project management. The

AHP measures logical consistency of judgments by means of a consistency ratio. Inconsistent judgments will lead to inconsistent results and should be re-evaluated. The consistency is perfect if all judgments relate to each other in a consistent way. If the project manager prefers cost performance to schedule 2 times with respect to the overall project performance, and prefers schedule to team satisfaction 2 times, then when he compares cost with team satisfaction the perfect judgment must be 4. The greater the deviation from 4, the greater is the inconsistency. Perfect consistency is achieved if all judgments are consistent, or in mathematical terms, matrix A in Table 2.12 satisfies the "cardinal" consistency property:

$$a_{ij}*a_{jk} = a_{ik} \qquad i, j,k = 1,........,8 \qquad \text{Equation (2.26)}$$

If a positive matrix A is consistent, then each row is a positive multiple of any given row. It should be noted that moving towards consistency does not necessarily mean moving closer to the "real" solution. A perfectly consistent judgment matrix can be constructed without any relation to reality. Thus consistency of judgments is a necessary condition to obtain a valid outcome but not sufficient; the project manager needs to validate the priority weights of the performance indices and check their practicality. If the solution arrived at through AHP does not appear right to an experienced, well-informed project manager, then he or she should restructure the hierarchy and/or improve the judgments.

Perfect consistency should not be forced in the pair-wise comparison matrix. Rather, the decision-makers should guess their judgments based on experience in all the cells except the diagonal ones where $a_{ii} = 1$ and the reciprocal cells where $a_{ij} = 1/a_{ij}$. Project team members may not be perfectly consistent, but that is the way they tend to evaluate the project performance. It should be noted that in a positive reciprocal matrix, the Eigen vector is insensitive to small changes in judgment and is stable (Saaty 1990).

Judgments are established through group discussion or by means of a questionnaire. When the management team participates in a discussion, the group may reach consensus in some comparisons; but when they differ, the geometric mean of their judgments is taken or by voting on the proposed values. This is due to the fact that judgments and their reciprocals must be viewed symmetrically. The reciprocal of the geometric mean of a set of judgments is the geometric mean of the reciprocals. This is not true of the arithmetic mean.

2.7.4 Consistency Measurement

To measure consistency, Saaty proposed The Consistency Index (CI) as a measure of the consistency or reliability of judgments made by the experts (Saaty1982). CI is defined as:

$$CI = \mu \equiv \frac{\lambda_{\max} - n}{n-1} \qquad \text{Equation (2.27)}$$

A positive reciprocal matrix is consistent if and only if $\lambda_{\max} = n$ then CI = 0 and perfect consistency is attained. A certain degree of inconsistency exists when $\lambda_{\max} \geq n$, this follows that CI > 0. For further details refer to Saaty (1990).

If the value of CI is compared to the Random Consistency Index (RC) for the same size matrix, where judgments were made at random, we obtain the consistency ratio (CR) which is expressed as:

$$CR = \frac{CI}{RC} \qquad \text{Equation (2.28)}$$

RC was calculated at the Wharton School for various sizes of matrices (up to the order of 15) as per the following table (Saaty 1982):

Table 2. 18 Random Consistency Index Table

Size of Matrix (n)	Random Consistency (RC)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.53
13	1.56
14	1.57
15	1.59

Saaty introduced the Consistency Ratio (CR) index as a quantitative measure of the logical harmony of judgments. A CR value greater than 0.1 indicates unreliable or non-consistent judgments. When experts compare many attributes, it is very challenging, especially in case of intangible criteria, to arrive at judgments that fall within the boundaries of the logical acceptance zone. In case of non-consistency, experts have to re-evaluate their opinions to satisfy the mathematical constraint suggested by Saaty.

Inconsistency Algorithme

Allouche et al. (2005a) proposed an algorithm using heuristics to solve the inconsistency problem of the judgment matrices within AHP. The suggested methodology will guarantee consistency of judgments without re-concurring with the experts by automatically adjusting the less certain comparisons while preserving the most certain judgments. This mechanism is based on minimal distortion to the experts' judgments and uses an iterative process to improve the consistency of judgments. The methodology uses the concept of *Basic Judgment Matrix* and requires experts to provide a minimal number of *basic values,* or most certain judgments, and the remaining less certain judgments are the *non-basic values*. The reader is referred to the referenced report for further details.

2.8 Interdependence between the performance indices

It has been assumed so far that the performance indices are independent and based on this assumption the priority weights were calculated. But often the indices at the same level of the hierarchy are interdependent. This interaction must be assessed and considered when computing the final priorities. In reality, a project is a complex system of interacting components. The profitability, for example, depends on cost and cost is influenced by quality performance, which impacts the client satisfaction. The following are few examples of the many interactions that can exist among the project performance indices:

- Both cost and profitability contribute to the project performance, but cost also influences profitability by contributing to the profit margin. As cost tends to increase profitability tends to decrease.
- Schedule performance may influence cost. Poor schedule performance will lead to lower labor productivity and higher material costs (to expedite delivery) leading to increase in costs.
- Quality performance influences cost performance. A high Construction Field Rework Index (CFRI) will increase the cost of rework and as a result the cost performance declines.
- Safety performance may influence both cost and schedule. A poor safety record may require additional measures to prevent future accidents and this might increase the costs and negatively impact the schedule performance.
- Safety, Quality, and Schedule performances influence the client satisfaction. Poor performance in these three areas will most probably decrease the client satisfaction.

The above existing dependencies between the competing indices will generate, in many cases, conflict and lower the overall performance index. In Chapter Five, TRAC, a conflict resolution methodology, is proposed to minimize or completely remove the negative impacts thus leading to improved project performance.

The correlation matrix in Table 2.19 reflects the level of interdependence among the eight performance indices namely, cost, schedule, billing, profitability, safety, quality, team and client satisfaction for a typical project. The level of correlation will definitely vary from project to another.

H = High correlation, M = Medium correlation, L = Low correlation, N = Negligible

Table 2. 19 Performance Correlation Matrix

Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
CPI	■	M	N	H	L	M	L	N
SPI	M	■	N	M	L	M	L	M
BPI	N	N	■	N	N	N	L	N
PPI	H	M	N	■	L	M	L	N
SFI	L	L	N	L	■	N	L	H
QPI	M	M	N	M	N	■	L	H
TSI	L	L	L	L	L	L	■	N
CSI	N	M	N	N	H	H	N	■

Two approaches are proposed to handle interdependence among attributes at the same level of the hierarchy. The first approach incorporates the impact of interdependence through subjective judgment and pair-wise comparison. In the correlation matrix shown above, safety influences cost, schedule and client satisfaction, thus safety will be assigned a higher priority relative to the other indices. This approach is practical and is preferred by many practitioners because it ignores the very complex mathematical adjustment for interdependence and simply relies on their own judgment.

2.8.1 Interdependence within the Analytical Hierarchy Process (AHP)

In many cases, the factors at the same level of the hierarchy are interdependent. This interaction between the various factors must be assessed and considered when computing the final priorities. Saaty mentioned two types of interdependence: additive interdependence and synergistic interdependence. In additive interdependence, each factor contributes a share that is uniquely its own and also contributes indirectly by overlapping or interacting with other factors (Saaty 1982). In this case, the total weight of the factor is the self-contribution due to its independent properties plus its contribution to other factors due to interaction. In synergistic interdependence, the impact of the interaction of the factors is greater than the sum of the impacts of the factors.

The analytical hierarchy process provides a simple method for measuring interdependence among factors. Saaty proposes that each factor becomes an objective and all the other factors are compared according to their contributions to that factor. This results in a set of contribution weights indicating the magnitude of contribution of the *(n-1)* factors with respect to the other factor. These priorities are then weighted by the independence priority of each related factor and the results are summed over each row to give the interdependence weights. Saaty demonstrated the concept of interdependence among factors in a numerical example using a two-level hierarchy (Saaty 1982). In that example, the success of a person is the objective and hard work (*HW*), productivity (*PR*), intelligence (*I*), and perseverance (*PE*) are the factors contributing to that objective. The independence vector of priorities was calculated using the maximum Eigen value. To handle the case of interdependence, Saaty assumed that each factor does not contribute to itself, or in other words each factor is totally dependent on the other factors.

If we apply the same methodology to our case, table 2.20 illustrates the case where safety is the objective and all the other seven indices are compared with respect to their contribution to the safety performance index. This generates a set of dependence priority weights indicating the influence of safety on all the other performance indices.

Table 2. 20 Judgment Matrix: Comparison of all other performance indices with respect to their contribution to safety

SFI	CPI	SPI	BPI	PPI	QPI	TSI	CSI
CPI	**1**	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}
SPI	$1/a_{12}$	**1**	a_{23}	a_{24}	a_{25}	a_{26}	a_{27}
BPI	$1/a_{13}$	$1/a_{23}$	**1**	a_{34}	a_{35}	a_{36}	a_{37}
PPI	$1/a_{14}$	$1/a_{24}$	$1/a_{34}$	**1**	a_{45}	a_{46}	a_{47}
QPI	$1/a_{15}$	$1/a_{25}$	$1/a_{35}$	$1/a_{45}$	**1**	a_{56}	a_{57}
TSI	$1/a_{16}$	$1/a_{26}$	$1/a_{36}$	$1/a_{46}$	$1/a_{56}$	**1**	a_{67}
CSI	$1/a_{17}$	$1/a_{27}$	$1/a_{37}$	$1/a_{47}$	$1/a_{57}$	$1/a_{67}$	**1**

If the above is repeated for all the remaining indices we obtain the dependence matrix as shown in Table 2.21, where the contribution of each factor to itself is zero.

Table 2. 21 Matrix of dependence priorities

Indices	**CPI**	**SPI**	**BPI**	**PPI**	**SFI**	**QPI**	**TSI**	**CSI**
CPI	**0**	$V1_{SPI}$	$V1_{BPI}$	$V1_{PPI}$	$V1_{SFI}$	$V1_{QPI}$	$V1_{TSI}$	$V1_{CSI}$
SPI	$V1_{CPI}$	**0**	$V2_{BPI}$	$V2_{PPI}$	$V2_{SFI}$	$V2_{QPI}$	$V2_{TSI}$	$V2_{CSI}$
BPI	$V2_{CPI}$	$V2_{SPI}$	**0**	$V3_{PPI}$	$V3_{SFI}$	$V3_{QPI}$	$V3_{TSI}$	$V3_{CSI}$
PPI	$V3_{CPI}$	$V3_{SPI}$	$V3_{BPI}$	**0**	$V4_{SFI}$	$V4_{QPI}$	$V4_{TSI}$	$V4_{CSI}$
SFI	$V4_{CPI}$	$V4_{SPI}$	$V4_{BPI}$	$V4_{PPI}$	**0**	$V5_{QPI}$	$V5_{TSI}$	$V5_{CSI}$
QPI	$V5_{CPI}$	$V5_{SPI}$	$V5_{BPI}$	$V5_{PPI}$	$V5_{SFI}$	**0**	$V6_{TSI}$	$V6_{CSI}$
TSI	$V6_{CPI}$	$V6_{SPI}$	$V6_{BPI}$	$V6_{PPI}$	$V6_{SFI}$	$V6_{QPI}$	**0**	$V7_{CSI}$
CSI	$V7_{CPI}$	$V7_{SPI}$	$V7_{BPI}$	$V7_{PPI}$	$V7_{SFI}$	$V7_{QPI}$	$V7_{TSI}$	**0**

In the above matrix, the vector $[V1_{SFI}, V2_{SFI}, V3_{SFI}, V4_{SFI}, 0, V5_{SFI}, V6_{SFI}, V7_{SFI}]$ represents the dependence priorities of the performance indices with respect to the Safety performance index. The interdependence priority vector is computed as per the following steps:

- To retain the same order of importance obtained in the case of independence, each column of the above contribution matrix is weighted element-wise by the independent priority of the corresponding factor. If we assume that the vector of independence priorities is $[v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8]$ for [CPI, SPI, BPI, PPI, SFI, QPI, TSI, CSI] respectively. For example, the column corresponding to SFI $[V1_{SFI}, V2_{SFI}, V3_{SFI}, V4_{SFI}, 0, V5_{SFI}, V6_{SFI}, V7_{SFI}]$ is multiplied by the independent priority of (SFI), v_5, to result in the weighted contribution column $[v_5{*}V1_{SFI}, v_5{*}V2_{SFI}, v_5{*}V3_{SFI}, v_5{*}V4_{SFI}, v_5{*}0, v_5{*}V5_{SFI}, v_5{*}V6_{SFI}, v_5{*}V7_{SFI}]$. Repeating the same calculations for (CPI), (SPI), (BPI), (PPI), (QPI), (TSI), and (CSI) will yield the following *weighted contribution matrix* as shown in Table 2.22.

Table 2. 22 Weighted Contribution Matrix

Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
CPI	**0**	$V_2{*}V1_{SPI}$	$v_3{*}V1_{BPI}$	$v_4{*}V1_{PPI}$	$v_5{*}V1_{SFI}$	$v_6{*}V1_{QPI}$	$v_7{*}V1_{TSI}$	$v_8{*}V1_{CSI}$
SPI	$v_1{*}V1_{CPI}$	**0**	$v_3{*}V2_{BPI}$	$v_4{*}V2_{PPI}$	$v_5{*}V2_{SFI}$	$v_6{*}V2_{QPI}$	$v_7{*}V2_{TSI}$	$v_8{*}V2_{CSI}$
BPI	$v_1{*}V2_{CPI}$	$V_2{*}V2_{SPI}$	**0**	$v_4{*}V3_{PPI}$	$v_5{*}V3_{SFI}$	$v_6{*}V3_{QPI}$	$v_7{*}V3_{TSI}$	$v_8{*}V3_{CSI}$
PPI	$v_1{*}V3_{CPI}$	$V_2{*}V3_{SPI}$	$v_3{*}V3_{BPI}$	**0**	$v_5{*}V4_{SFI}$	$v_6{*}V4_{QPI}$	$v_7{*}V4_{TSI}$	$v_8{*}V4_{CSI}$
SFI	$v_1{*}V4_{CPI}$	$V_2{*}V4_{SPI}$	$v_3{*}V4_{BPI}$	$v_4{*}V4_{PPI}$	**0**	$v_6{*}V5_{QPI}$	$v_7{*}V5_{TSI}$	$v_8{*}V5_{CSI}$
QPI	$v_1{*}V5_{CPI}$	$V_2{*}V5_{SPI}$	$v_3{*}V5_{BPI}$	$v_4{*}V5_{PPI}$	$v_5{*}V5_{SFI}$	**0**	$v_7{*}V6_{TSI}$	$v_8{*}V6_{CSI}$
TSI	$v_1{*}V6_{CPI}$	$V_2{*}V6_{SPI}$	$v_3{*}V6_{BPI}$	$v_4{*}V6_{PPI}$	$v_5{*}V6_{SFI}$	$v_6{*}V6_{QPI}$	**0**	$v_8{*}V7_{CSI}$
CSI	$v_1{*}V7_{CPI}$	$V_2{*}V7_{SPI}$	$v_3{*}V7_{BPI}$	$v_4{*}V7_{PPI}$	$v_5{*}V7_{SFI}$	$v_6{*}V7_{QPI}$	$v_7{*}V7_{TSI}$	**0**

- The interdependent weight of a factor is defined by the magnitude of contribution to itself and contribution to other factors. For example, the interdependent weight of Safety Performance (SFI) is obtained by summing up the self-contribution weight of (SFI), zero in this case, and the contribution of (SFI) to (CPI), (SPI), (BPI), (PPI), (QPI), (TSI), and (CSI) which has a magnitude of $v_1*V4_{CPI} + v_2*V4_{SPI} + v_3*V4_{BPI} + v_4*V4_{PPI} + v_6*V5_{QPI} + v_7*V5_{TSI} + v_8*V5_{CSI}$. Now adding each row of the weighted contribution matrix will generate the vector of dependence priorities as shown in Table 2.23.

Table 2. 23 Inter-dependence Priorities or Weights

Index	**Dependence Priorities**
CPI	$=0+v_2*V1_{SPI}+v_3*V1_{BPI}+v_4*V1_{PPI}+v_5*V1_{SFI}+v_6*V1_{QPI}+v_7*V1_{TSI}+v_8*V1_{CSI}$
SPI	$=v_1*V1_{CPI}+0+v_3*V2_{BPI}+v_4*V2_{PPI}+v_5*V2_{SFI}+v_6*V2_{QPI}+v_7*V2_{TSI}+v_8*V2_{CSI}$
BPI	$=v_1*V2_{CPI}+v_2*V2_{SPI}+0+v_4*V3_{PPI}+v_5*V3_{SFI}+v_6*V3_{QPI}+v_7*V3_{TSI}+v_8*V3_{CSI}$
PPI	$=v_1*V3_{CPI}+v_2*V3_{SPI}+v_4*V3_{BPI}+0+v_5*V4_{SFI}+v_6*V4_{QPI}+v_7*V4_{TSI}+v_8*V4_{CSI}$
SFI	$=v_1*V4_{CPI}+v_2*V4_{SPI}+v_3*V4_{BPI}+v_4*V4_{PPI}+0+v_6*V5_{QPI}+v_7*V5_{TSI}+v_8*V5_{CSI}$
QPI	$=v_1*V5_{CPI}+v_2*V5_{SPI}+v_3*V5_{BPI}+v_4*V5_{PPI}+v_5*V5_{SFI}+0+v_7*V6_{TSI}+v_8*V6_{CSI}$
TSI	$=v_1*V6_{CPI}+v_2*V6_{SPI}+v_3*V6_{BPI}+v_4*V6_{PPI}+v_5*V6_{SFI}+v_6*V6_{QPI}+0+v_8*V7_{CSI}$
CSI	$=v_1*V7_{CPI}+v_2*V7_{SPI}+v_3*V7_{BPI}+v_4*V7_{PPI}+v_5*V7_{SFI}+v_6*V7_{QPI}+v_7*V7_{TSI}+0$

Discussion

The above methodology assumed the concept of total dependence, which is not applicable in our case since every performance index will contribute to itself as well as to the remaining indices. Inspired by Saaty's idea of interaction among factors, Allouche et al. (2005b) generalized the concept of interdependence and introduced the concept of self-contribution to address cases in which dependency among factors is not total. This study recommends the model developed by Allouche et al. (2005b) to account for interdependence as will be explained in the next section.

2.8.2 Measurement of Interdependence Weights – Mathematical Approach

In the following discussion, a mathematical model is proposed to calculate the interdependence set of weights for the eight performance indices based on the methodology proposed by Allouche et al. (2005b). In this study, Allouche et al. (2005b) introduced the notion of self-contribution of an element to the overall performance of the system that is composed of all the elements.

Self-contribution

The *self-contribution* of a performance index to the overall performance of a project represents a level of *independency* of this index from the other performance indices contributing to the project performance. For example, if safety performance is not affected when other areas of performance are at their lowest levels of performance, then safety is considered independent and its weight is totally due to its self-contribution. However, most of the performance areas defined in this research are interdependent to a certain degree.

Given that each performance index could contribute to itself as well as receive contribution from other indices, the following notations are defined:

w_i = Weight of performance index I_i assuming independence, or the absolute weight of I_i for i=1,...8.

s_i = A fraction that represents the Self-contribution % of w_i for i=1,...8.

r_i = $(1-s_i)$ which is the remaining portion of w_i earned from the contribution of other indices to I_i.

c_i = $w_i * s_i$ which represents the self-contribution part to the absolute weight of Index I_i.

$w_i - c_i = (1 - s_i) * w_i$ which represents the contribution of other indices to the Index I_i.

To each *Level Of Impact* (*LOI*), on a scale of 100, a *Measure of Dependency* (r_i) can be associated. A scale relating *LOI*, r_i, and s_i is proposed in Table 2.24. The self-contribution weight can be determined by answering the following question:

"What is the impact of all other performance indices I_j on the index I_i when I_j are at their lowest performance levels?"

Usually experienced project team members are able to provide answers. A proposed scale is shown in Table 2.15. To illustrate the concept of self-contribution, say for safety, the project team should answer the following question:

"What is the impact of all other performance indices (CPI, SPI, BPI, PPI, QPI, TSI, CSI) on the Safety Performance Index (SFI) when (CPI, SPI, BPI, PPI, QPI, TSI, CSI) are at poor performance levels?"

Most likely, if the project is well behind schedule (poor SPI), the activities will be crashed and the site will be busy with labor and equipment, as a result, the chances of incidents occurring in a congested site increase. On the other hand, if the project is way over budget, the budget allocated for safety tools and training could be impacted and consequently the safety performance might drop. The impact of poor performance in BPI, PPI, QPI, TSI, and CSI on safety could be very minimal. Based on this, we can say that the overall impact on SFI is *minimal* and the self-contribution is 80% using table 2.24. It should be emphasized that this scale will vary from one project to another within the same company and is proposed for illustration purposes only.

Table 2. 24 Level Of Impact (LOI) scale

Level of Impact (LOI)	Measure of Dependency % (r_i)	Self-Contribution % ($s_i = 1-r_i$)
Nil	0	100
Minimal	20	80
Moderate	40	60
Strong	60	40
Very Strong	80	20
Absolute	100	0

The self-contribution part of each performance index and the contribution received from the other interacting indices can be represented by the following matrix equation:

$$[w] = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_i \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} s_1 w_1 \\ s_2 w_2 \\ \vdots \\ s_i w_i \\ \vdots \\ s_n w_n \end{bmatrix} + \begin{bmatrix} (1-s_1)w_1 \\ (1-s_2)w_2 \\ \vdots \\ (1-s_i)w_i \\ \vdots \\ (1-s_n)w_n \end{bmatrix} \qquad \text{Equation (2.29)}$$

Contribution Matrix

In the case of inter-dependence, each performance index becomes an objective and all the other indices are compared with respect to their contributions to that performance index. For example, Table 2.25 reflects the relative contribution of indices (*SPI, BPI, PPI, SFI, QPI, TSI, and CSI*) with respect to the Cost Performance Index (*CPI*).

Table 2. 25 Relative contribution matrix with respect to the Cost Performance Index

$$\begin{array}{c|ccccccc}
\boldsymbol{CPI} & SPI & BPI & PPI & SFI & QPI & TSI & CSI \\
\hline
SPI & 1 & c_{23} & c_{24} & c_{25} & c_{26} & c_{27} & c_{28} \\
BPI & c_{32} & 1 & c_{34} & c_{35} & c_{36} & c_{37} & c_{38} \\
PPI & c_{42} & c_{43} & 1 & c_{45} & c_{46} & c_{47} & c_{48} \\
SFI & c_{52} & c_{53} & c_{54} & 1 & c_{56} & c_{57} & c_{58} \\
QPI & c_{62} & c_{63} & c_{64} & c_{65} & 1 & c_{67} & c_{68} \\
TSI & c_{72} & c_{73} & c_{74} & c_{75} & c_{76} & 1 & c_{78} \\
CSI & c_{82} & c_{83} & c_{84} & c_{85} & c_{86} & c_{87} & 1
\end{array}$$

Calculating the Eigen vector for the matrix in Table 2.25 yields a priority vector that reflects the magnitude of contribution of each performance index (*SPI, BPI, PPI, SFI, QPI, TSI, and CSI*) with respect to the Cost Performance Index (*CPI*).

This *(7 x1)* vector is noted by:

$$W^1_{2...8} = \begin{bmatrix} w_{21} \\ w_{31} \\ w_{41} \\ w_{51} \\ w_{61} \\ w_{71} \\ w_{81} \end{bmatrix}_{7\mathrm{x}1} \qquad \text{Equation (2.30)}$$

The above equation can be written as: $W^1_{2...8} = \left[W^1{}_{j\neq 1}\right]_{7\mathrm{x}1}$

In general, we can write:

$$W^i_{j\neq i} = \left[W_{ji}\right]_{7\mathrm{x}1} \qquad \text{For } i = 1, \ldots, 8, \text{ and } j = 1,\ldots,8. \quad j \neq i \qquad \text{Equation (2.31)}$$

By adding the self-contribution weight w_{ii} to the *(7x1)* vector of Equation (2.31) we obtain an *8x1* vector as shown in Equation (2.32). Note that w_{ii} for $i = 1,...,8$, is not necessarily zero:

$$W_j^i = \left[W_{ji}\right]_{8x1} \qquad \text{For } i = 1, \ldots, 8, \text{ and } j = 1,\ldots,8. \qquad \text{Equation (2.32)}$$

Repeating the above procedure for the remaining indices (*SPI, BPI, PPI, SFI, QPI, TSI, and CSI*) will generate a set of priorities indicating the relative contribution of each index to all the other indices. The columns of the ***contribution matrix*** in Table 2.26 are the *8x1* vectors shown in Equation 2.32.

Table 2. 26 Contribution Matrix

$$[C] = \begin{array}{c|cccccccc|} PI & CPI & SPI & BPI & PPI & SFI & QPI & TSI & CSI \\ \hline CPI & \boldsymbol{w_{11}} & w_{12} & w_{13} & w_{14} & w_{15} & w_{16} & w_{17} & w_{18} \\ SPI & w_{21} & \boldsymbol{w_{22}} & w_{23} & w_{24} & w_{25} & w_{26} & w_{27} & w_{28} \\ BPI & w_{31} & w_{32} & \boldsymbol{w_{33}} & w_{34} & w_{35} & w_{36} & w_{37} & w_{38} \\ PPI & w_{41} & w_{42} & w_{43} & \boldsymbol{w_{44}} & w_{45} & w_{46} & w_{47} & w_{48} \\ SFI & w_{51} & w_{52} & w_{53} & w_{54} & \boldsymbol{w_{55}} & w_{56} & w_{57} & w_{58} \\ QPI & w_{61} & w_{62} & w_{63} & w_{64} & w_{65} & \boldsymbol{w_{66}} & w_{67} & w_{68} \\ TSI & w_{71} & w_{72} & w_{73} & w_{74} & w_{75} & w_{76} & \boldsymbol{w_{77}} & w_{78} \\ CSI & w_{81} & w_{82} & w_{83} & w_{84} & w_{85} & w_{86} & w_{87} & \boldsymbol{w_{88}} \end{array}$$

Now maintaining the same order of importance established in the case of independence, the above priorities w_{ij} in Table 2.26 are then weighted according to the absolute weight w_i for $i = 1,....,8$. The self-contribution weight is calculated as $w_{jj} = w_j * s_j = c_j$ for $j = 1,....,8$. For example, the self-contribution of the Cost Performance Index (CPI) is $w_{11} = w_1 * s_1 = c_1$. This constitutes the first coefficient in the first column of the *weighted contribution matrix*. The remaining entries of the first column ($j=1$) represent the contribution of each of the seven performance index (*SPI, BPI, PPI, SFI, QPI, TSI, and*

CSI) to the Cost Performance Index (CPI) calculated as $w_{i1}*w_1*(1-s_1)$ for $i = 2,....,8$. Applying the same calculations to the remaining columns ($j= 2,...,8$) will result in the *weighted contribution matrix* as shown in Table 2.27.

Table 2. 27 Weighted Contribution Matrix

$$\begin{array}{c|cccccccc}
PI & CPI & SPI & \ldots & \ldots & \ldots & \ldots & \ldots & CSI \\
\hline
CPI & c_1 & w_{12}*w_2*(1-s_2) & \ldots & \ldots & \ldots & \ldots & \ldots & w_{18}*w_8*(1-s_8) \\
SPI & w_{21}*w_1*(1-s_1) & c_2 & \ldots & \ldots & \ldots & \ldots & \ldots & w_{28}*w_8*(1-s_8) \\
BPI & w_{31}*w_1*(1-s_1) & w_{32}*w_2*(1-s_2) & c_3 & \ldots & \ldots & \ldots & \ldots & w_{38}*w_8*(1-s_8) \\
PPI & w_{41}*w_1*(1-s_1) & w_{42}*w_2*(1-s_2) & \ldots & c_4 & \ldots & \ldots & \ldots & w_{48}*w_8*(1-s_8) \\
SFI & w_{51}*w_1*(1-s_1) & w_{52}*w_2*(1-s_2) & \ldots & \ldots & c_5 & \ldots & \ldots & w_{58}*w_8*(1-s_8) \\
QPI & w_{61}*w_1*(1-s_1) & w_{62}*w_2*(1-s_2) & \ldots & \ldots & \ldots & c_6 & \ldots & w_{68}*w_8*(1-s_8) \\
TSI & w_{71}*w_1*(1-s_1) & w_{72}*w_2*(1-s_2) & \ldots & \ldots & \ldots & \ldots & c_7 & w_{78}*w_8*(1-s_8) \\
CSI & w_{81}*w_1*(1-s_1) & w_{82}*w_2*(1-s_2) & \ldots & \ldots & \ldots & \ldots & \ldots & c_8
\end{array}$$

Interdependence priorities

Each column of the matrix in Table 2.27 must sum up to the absolute weights as shown in the following equation:

$$w_j = c_j + \sum_{\substack{i=1 \\ i \neq j}}^{8} w_{ij} * w_j * (1 - s_j) \qquad \text{For } j = 1,..., 8 \qquad \text{Equation (2.33)}$$

As shown previously, the interdependence priorities or the actual weights are derived from the self-contribution and the contribution to other performance indices and thus they are obtained by summing up the rows of the weighted distribution matrix in Table 2.27. If $\boldsymbol{p}$ is the vector representing the weights or priorities for the eight performance indices in case of interdependence, then $\boldsymbol{p} = (p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8)$ is calculated by adding up row j for $j= 1,...,8$ as shown in Equation (2.34):

$$p_j = w_j s_j + \sum_{\substack{i=1 \\ i \neq j}}^{8} w_{ji} * w_i * (1 - s_i) \qquad \text{For } j = 1,..., 8 \qquad \text{Equation (2.34)}$$

The interdependency vector denoted by $p = (p_1,...,p_8)$, as opposed to the independent vector of weights $w = (w_1,...,w_8)$, reflects the degree of dependency or interactions among the performance indices and must be used to indicate the *actual* weights of the indices. These two vectors may differ significantly and consequently could have different meaning and implications in the decision-making process.

Special case:

Total Independence: This is the case where the performance indices are totally contributing to themselves. The case of complete independence for all the eight indices is not common in real life construction projects. With total independence the self-contribution is 100% or $s_i = 100$ for $i= 1,...,8$ and the vector of weights or priorities in equation (2.34) can be reduced to equation (2.35):

$$p_j = w_j \qquad \text{For } j = 1,...,8 \qquad \text{Equation (2.35)}$$

2.9 AHP Model with Range Judgments

The proposed model used standard AHP (Saaty 1982) that is based on a deterministic approach in the sense that judgments were expressed in a linguistic scale and then translated into a numerical value. The result of the deterministic model was a list of priority weights for the set of performance indices as explained in section 2.7. Although the vast majority of pervious AHP applications used the deterministic approach, the proposed AHP model can also be extended to deal with problems in a probabilistic way. In the probabilistic version, the point judgments by the experts are substituted with range judgments of specified probability distribution function, i.e. the expert will provide a lower and an upper bound for his/her judgment. Range judgments are helpful to represent the uncertainty of the individual expert and in case of lack of consensus and/or dispersion of judgments in a group discussion.

In the probabilistic approach, judgments are random variables and so are the priority weights for the eight performance indices. Single value priorities in the deterministic approach, are replaced by a mean and a standard deviation using Monte Carlo simulation. At each run, a set of point judgments is extracted from the specified interval judgments, and if consistent, priority weights for the performance indices are derived using the standard AHP procedure as outlined in section 2.7. The number of runs should be sufficient to obtain a satisfactory level of confidence in the output result. A flowchart for the proposed Monte Carlo simulation approach is shown in Figure 2.10.

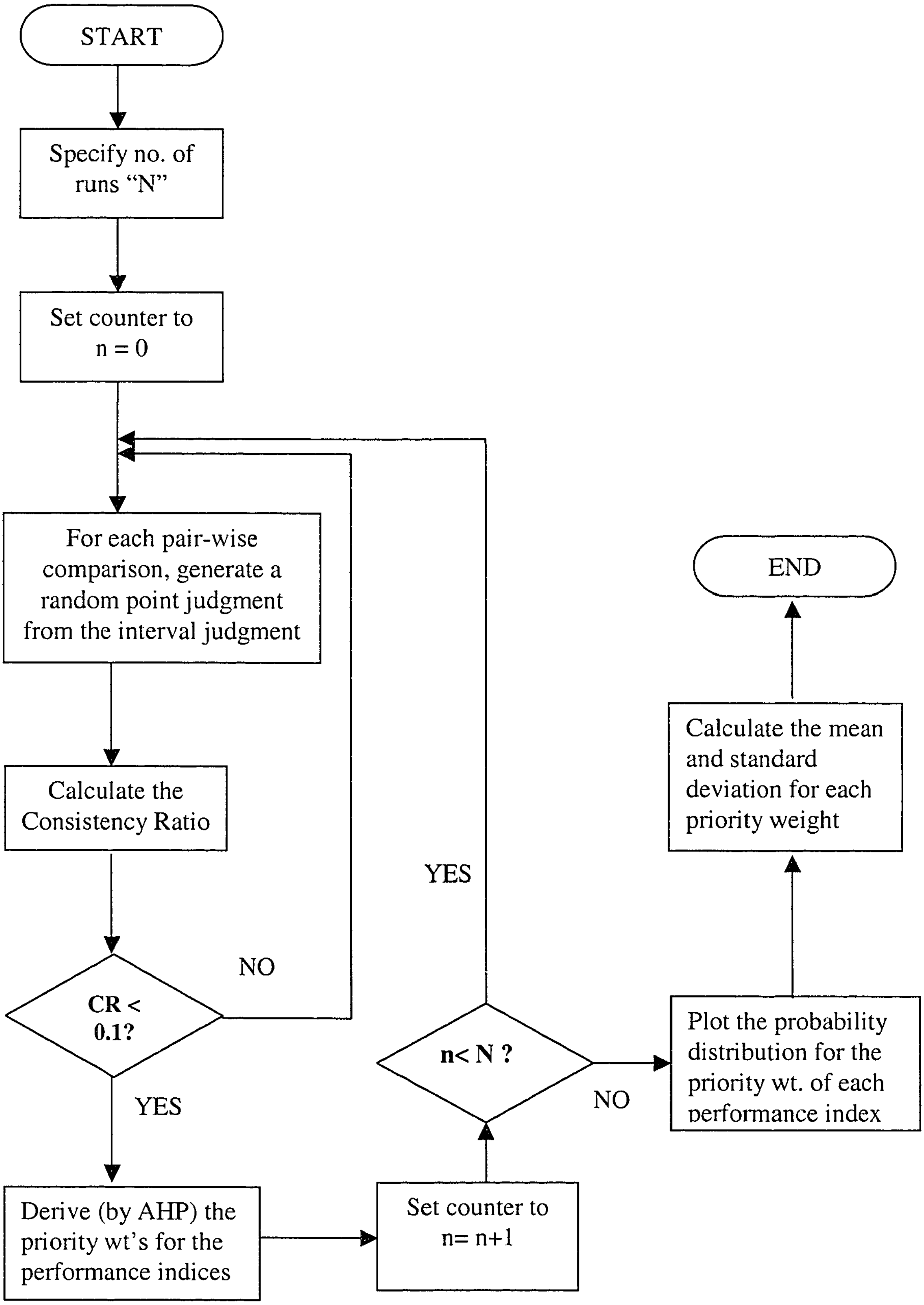


Figure 2. 10 Flowchart for the Monte Carlo simulation approach for range judgments

2.10 Advantages of the Integrated Project Performance Evaluation Model (IPPM)

The proposed methodology provides a systematic and structured process to evaluate project performance. The concept of project success is defined with respect to clear set of goals and objectives. Despite the complexities of measuring project performance, the concept was quantified into a meaningful index that is based on measured objective data. The advantages of this research can be summarized as follows:

- Introduction of a tool that allows managers of construction projects to evaluate the performance of projects in a formal and systematic way. It helps them to identify and set relative weights on the basis of their objectives and their knowledge and experience. The model is very flexible and can be adapted to meet the specific requirements of any construction project. Consistent and quantitative measurement of performance leads to better variance analysis and consequently effective project control and achievement of project objectives.

- The consistent historical performance data can be utilized in future projects to improve planning and effective implementation of project execution processes.

- A composite performance index can provide an overall project performance status. In addition, by determining the individual performance indices, the project management team can effectively communicate to their staff the project status and future priorities in each area.

- The proposed framework organizes the intuitive judgments and standardizes performance measurement. Proper and timely performance measurement allows the generation of proper feedback that is needed to implement corrective action. In addition, the project performance equation will allow contractors to compare the success of two or more projects within their organization for benchmarking purposes. Also, they can compare the success in similar individual areas of performance.

It should be mentioned that this study is proposing a methodology so that practitioners as well as researchers can utilize to develop a customized project performance index for projects of any type or size.

2.11 Conclusion

Under the current levels of competition, projects are being implemented in complex, dynamic, and uncertain environments. As project management is getting more integrated, performance measurement of projects is expanding to include more aspects of performance. As a result, contractors who are project-oriented organizations need to use a unified performance measurement system that integrates all project attributes.

A framework for project performance measurement was developed to formalize the way contractors evaluate projects and assist in controlling projects during the execution phase. The new methodology measures separately the performance of all the critical objectives of a project as well as the overall performance. The system will be able to draw the attention of management to poor performance in every dimension, and the project manager will be able to realize the extent of its impact on achieving the project objectives. The IPPM combines all dimensions of project performance in one overall index equation by assigning a priority or weight to each dimension. The overall index is based on eight objective measurements of project performance: cost, schedule, billing, profitability, safety, quality, team satisfaction, and client satisfaction. These indices were considered of major significance and necessitated measurement and close monitoring by the project management team. The performance index presented in this chapter should be considered by any construction organization that needs to measure the success of its projects. An AHP model was proposed to facilitate the quantification of the project performance priorities and to derive the overall project performance index. This index would best reflect the health of construction projects at the management level as well as at the operational level. The model is simple to use and the computations can be run using any spreadsheet program. The model design allows the user, as per his/her needs and preferences to determine the priority or the contribution of the eight performance factors to the project performance. It structures the project management team's knowledge and experience and incorporates it with a practical performance measurement tool.

As every construction project is unique, it is necessary for the contractor to evaluate the applicability of the proposed performance hierarchy for each project prior to implementation. This chapter presents a framework for an integrated project performance evaluation system to assist project/construction managers monitor and control progress of projects by evaluating eight sets of indices. The proposed model recommends hierarchic evaluation of performance indices and sub-indices by utilizing the Analytical Hierarchy Process (AHP). This model framework and AHP allow analysis of both quantifiable and non-quantifiable performance attributes that are significant in the project evaluation and monitoring process.

One of the various benefits of the proposed system is the systematic measurement and analysis of project performance attributes. This ensures that all relevant and significant criteria for evaluating projects have been considered leading to a more reliable and comprehensive performance benchmarking of projects. Since practitioners have different interests, and objectives of construction performance, this model is flexible enough to be tailored to meet their specific needs.

REFERENCES

Abba, W. F., (1995). "Beyond Communicating with Earned Value: Managing Integrated Cost, Schedule and Technical Performance." *Project Management Institute Annual Seminar / Symposium*, New Orleans, 16-18th October, pp. 2-6.

Ahuja, H., (1976). *Construction performance control by networks*, Wiley, New York.

Al Khalil, Mohammed I. (2002). "Selecting the appropriate project delivery method using AHP." *International Journal of Project Management*, 20(6), 469-474.

Alarcon, Luis F., and Ashley, David B., (1996). "Modeling Project Performance for Decision Making." *Journal of Construction Engineering and Management*, ASCE, 122(3), 265-273.

Allouche, M., Nassar, N., and AbouRizk, S., (2005a). "A suggested algorithm to solve the inconsistency problem within the Analytical Hierarchy Process methodology." Internal Report through the NCERC/Alberta Construction Industry Research Chair.

Allouche, M., Nassar, N., Langevine, R., and AbouRizk, S., (2005b). "A quantitative approach to evaluate the impact of interdependence on priorities within the Analytical Hierarchy Process (AHP)." Internal Report through the NCERC/Alberta Construction Industry Research Chair.

Ashley, D. B., Lurie, C. S., and Jaselskis, E. J., (1987). "Determinants of construction project success." *Project Management Journal*, 18(2), 69-79.

Barraza, Gabriel A., Back, W. Edward, and Mata, Fernando, (2000). "Probabilistic Monitoring of Project *Performance Using SS-Curves." Journal of Construction Engineering and Management*, ASCE, 126(2), 142-148.

Boussabaine, A. H., (1995). "A neural network system for productivity forecasting." *Symposium of Automation and Robotics in Construction XII*, 375-381.

Boussabaine, A. H. and Duff, A. R., (1996). "An expert-simulation system for construction productivity forecasting." *Building Research and Information*, 24(5), 279-286.

Bunn, Derek W., (1982). *Analysis for Optimal Decisions*, John Wiley & Sons Ltd, New York.

Cagno, E., Caron, F., and Perego, A., (2001). "Multi-criteria Assessment of the Probability of Winning in the Competitive Bidding Process." *International Journal of Project Management*, 19(6), 313-324.

Chan, Felix T.S, Jiang Bing, and Tang, Nelson K.H. (2000). "The development of intelligent decision support tools to aid the design of flexible manufacturing systems." *International Journal of Production Economics*, 65 (1), 73-84.

Chao, Li-Chung, and Skibniewski, Miroslaw J. (1995). "Neural Network Method of Estimating Construction Technology Acceptability." *Journal of Construction Engineering and Management*, ASCE, 121 (1), 130-142.

Chao, L. and Skibniewski, M.J., (1994). "Estimating construction productivity-Neural Network based approach." *Journal of Computing in Civil Engineering*, 8(2), 234-251.

Cheng, Min-Yuan, Su, Cheng-Wei, and You, Horng-Yuh, (2003). "Optimal Project Organizational Structure for Construction Management." *Journal of Construction Engineering and Management*, ASCE, 129(1), 70-79.

Cheng, Eddie W. L., Li, Heng, and Love, P. E. D., (2000). "Establishment of Critical Success Factors for Construction Partnering." *Journal of Management in Engineering*, ASCE, 16(2), 84-92.

Cheung, Sai-On, Suen, Henry C. H., and Lam, Tsun-Ip, (2002). "Fundamentals of Alternative Dispute Resolution Processes in Construction." *Journal of Construction Engineering and Management*, ASCE, 128(5), 409-417.

Christensen, D.S., (1994). "A Review of Cost/Schedule Control Systems Criteria Literature." *Project Management Journal*, 25(3), 32-39.

Chua, D. K. H., Kog, Y. C., and Loh, P. K., (1999). "Critical Success Factors for Different Project Objectives." *Journal of Construction Engineering and Management*, ASCE, 125(3), 142-150.

Chua, D. K. H., Kog, Y. C., Loh, P. K., and Jaselskis, E. J., (1997). "Model for Construction Budget Performance – Neural Network Approach." *Journal of Construction Engineering and Management*, ASCE, 123(3), 214-222.

Cleland, D. I., (1986). "Measuring success: the owner's viewpoint." *1986 Proceedings, Project Management Institute*, Montreal, Canada, pp. 6-12.

Cleland, D. I., and King, W. R., (1988). *Project Management Handbook*, 2nd ed. by Van Nostrand-Reinhold, New York.

Cole, L. J. R., (1991). "Construction scheduling: Principles, Practices, and Six Case Studies." *Journal of Construction Engineering and Management*, ASCE, 117(4), 579-588.

Construction Industry Institute CII (1995) - *Pre-project Planning Handbook*.

de Falco, Massimo, and Macchiaroli, Roberto, (1998). "Timing of control activities in project planning." *International Journal of Project Management*, 16(1), 51-58.

de Wit, A., (1986). "Measuring project success: an illusion." *1986 Proceedings, Project Management Institute*, Montreal, Canada, 13-21.

Dey Prasanta Kumar, Tabucanon Mario T., and Ogunlana Stephen O. (1996). "Petroleum pipeline construction planning: a conceptual framework." *International Journal of Project Management*, 14(4), 231-240.

Dias, A., and Ioannou, P.G., (1996). "Company and project evaluation model for privately promoted infrastructure projects." *Journal of Construction Engineering and Management*, ASCE, 122(1), 71-82.

Dozzi, S.P., AbouRizk, S.M. and Schroeder, S. L., (1996). "Utility-theory model for bid markup decisions." Journal *of Construction Engineering and Management*, ASCE, 122(2), 119-124.

Dyson, R. G., and Foster, M. J., (1983). "Making Planning More Effective." *Long Range Planning*, pp. 68-73.

El-Mikawi, Mohamed, and Mosallam, Ayman S., (1996). "A methodology for evaluation of the use of advanced composites in structural civil engineering applications." *Composites part B: Engineering*, 27 (3-4), 203-215.

Elazouni, Ashraf M., and Gab-Allah, Ahmed A., (2004). "Finance-Based Scheduling of Construction Projects Using Integer Programming." *Journal of Construction Engineering and Management*, ASCE, 130(1), 15-24.

Fayek, A.R., Dissanayake, G.M., and Campero, O., (2003). "Measuring and Classifying Construction Field Rework: A Pilot Study." Internal Report, University of Alberta.

Fleming, Quentin W., and Koppelman, Joel M., (2002). "Using Earned Value Management." *Cost Engineering*, 44(9), 32-36.

Fleming, Q. W., and Koppelman, J. M., (2000). *Earned Value Project Management,* 2nd edition, Project Management Institute, Inc, USA.

Fleming, Quentin W., and Koppelman, Joel M., (1998). "Earned Value Project Management." *The Journal of Defense Software Engineering*, July 1998, 19-23.

Fleming, Q. W., and Koppelman, J. M., (1994). "The Essence of Evolution of Earned Value." *Cost Engineering*, AACE, 36(11), 21-27.

Flood, I. and Nabil, K., (1994). "Neural networks for civil engineering I and II." *Journal of Computing in Civil Engineering*, 8(2), 131-163.

Freeman, M. and Beale, P., (1992). "Measuring project success." *Project Management Journal*, 23(1), 8-16.

Gao, Zhili, Smith, Gary R., and Minchin, Edward R. Jr., (2002). "Budget and Schedule Success for Small Capital-Facility Projects." *Journal of Management in Engineering*, 18(4), 186-193.

Gardiner, Paul D., and Stewart, Kenneth, (2000). "Revisiting the golden triangle of cost, time and quality: the role of NPV in project control, success and failure." *International Journal of Project Management*, 18(4), 251-256.

Gibson, G. E., and Hamilton, M. R., (1994). *Analysis of pre-project planning effort and success variables for capital facility projects*, Source Document 105, Construction Industry Institute, University of Texas at Austin, Texas.

Goldfayl, G., (1995). "Cost/Schedule Techniques for Building Projects in Australia." *International Cost Engineering Council / Australian Institute of Quantity Surveyors Symposium*, Gold Coast, 21-23 May, pp. 143-161.

Gordon, C.M., (1994). "Choosing appropriate construction contracting method." *Journal of Construction Engineering and Management*, ASCE, 120(1), 196-210.

Griffith, Andrew F., Gibson, G. Edward Jr., Hamilton, Michele R., Tortora, Aniello L., and Wilson, Charles T., (1999). "Project Success Index for Capital Facility Construction Projects." *Journal of Performance of Constructed Facilities*, 13(1), 39-45.

Handa, V. and Adas, A., (1996). "Predicting the level of organizational effectiveness: a methodology for the construction firm." *Construction Management and Economics*, 14(4), 341-352.

Hastak, Makarand, (1998). "Advanced automation or conventional construction process?" *Journal of Automation in Construction*, 7(4), 299-314.

Jaselkis, Edward J. and Ashley, David B., (1999). "Preliminary Study on Contractor Success in Developing Countries." International Conference on Construction Industry Development, Singapore.

Jaselskis, E.J. and Ashley, D.B., (1991). "Optimal allocation of project management resources for achieving success." *Journal of Construction Engineering and Management*, ASCE, 117(2), 321-340.

Jolivet, F., and Batignolles, Spie, (1986). "The possibility of anticipating, several years in advance, the success or failure of a project." *1986 Proceedings, Project Management Institute*, Montreal, Canada, 35-39.

Kerzner, Harold, (1989). *Project Management: A Systems Approach to Planning, Scheduling and Controlling,* 3rd edition by Van Nostrand Reinhold, Melbourne, Australia.

Kothari, A. K., (1986). "Success in project management." *1986 Proceedings, Project Management Institute*, Montreal, Canada, 240-246.

Larson, E., (1995). "Project partnering: Results of study of 280 construction projects." *Journal of Management in Engineering*, ASCE, 11(2), 30-35.

Li, Ji, (2004). *Web-based Integrated Project Control*, Doctoral Dissertation, Concordia University, Montreal, Canada.

Lim, E.C., (1993). "Influence of management and labour on construction productivity in Singapore." *Building Res. and Information*, 12(5), 296-303.

Mali, Paul, (1986). *MBO Updated,* John Wiley & Sons, New York.

Meredith, J. R., and Mantel, S. J., (1995). *Project Management – A Managerial Approach*, 3rd ed., Wiley, New York.

Mohsini, R.A. and Davidson, C.H., (1992). "Determinants of performance in the traditional building process." *Construction Management and Economics*, 10(4), 343-359.

Morris, P., (1986). "Research at Oxford into the Preconditions of Success and Failure of Major Projects." *1986 Proceedings, Project Management Institute*, Montreal, Canada, 53-66.

Morris, P.W., and Hough, G. H., (1987). *Anatomy of major projects*, Wiley, New York.

Moselhi, O., (1991). "Integrated Time and Cost Control of Projects." *International Symposium on building performance*, January, Cairo, Egypt.

Murphy, D. C., Baker, B. N., and Fisher, D., (1974). *Determinants of Project Success*, Boston College School of Management, Boston.

Nassar, K., Thabet, Walid, and Beliveau, Yvan, (2003). "A procedure for multi-criteria selection of building assemblies." *Automation in Construction*, 12(5), 543-560.

Parker, Stephen K., and Skitmore, Martin, (2005). "Project Management turnover: causes and effects on project performance." *International Journal of Project Management*, 23(3), 205-214.

Partovi, Fariborz Y., and Burton, Jonathan. (1992). "An analytical hierarchy approach to facility layout." *Computers & Industrial Engineering*, 22(4), 447-457.

Pinnell, Steven S., (1980). "Construction/Engineering Management: a Comparison". *Issues in Engineering Journal of Professional Activities*, ASCE, 106(4), 405-413.

Pinto, J. K. and Slevin, D. P., (1992). *Project implementation profile*, Xicom, Tuxedo, New York.

Pinto, J. K. and Slevin, D. P., (1988). "Critical success factors across the project life cycle." *Project Management Journal*, 19 (3), 67-75.

PMI (PROJECT MANAGEMENT INSTITUTE), (1996). *A Guide to the Project Management Body of Knowledge (PMBOK)*, PMI, Upper Darby, PA.

Pocock, J.B., Hyun, C.T., Liu, L.Y. and Kim, M.K., (1996). "Relationship between project interaction and performance indicators." *Journal of Construction Engineering and Management*, ASCE, 122(2), 165-176.

Portas, J. and AbouRizk, S., (1997). "Neural Network Model for estimating construction productivity." *Journal of Construction Engineering and Management*, 123(2), 181-188.

Rad, Parviz F. (2003). "Project Success Attributes." *Cost Engineering*, 45 (4), 23-29.

Randolph, T. and Raynar, K.A., (1997). "Scheduled overtime and labor productivity: Quantitative analysis." *Journal of Construction Engineering and Management*, ASCE, 123(4), 399-410.

Raz, Tzvi, and Erel, Erdal, (2000). "Optimal timing of project control points." *European Journal of Operational Research*, 127(2), 252-261.

Rozenes, Shai, Vitner, Gad, and Spraggett, Stuart, (2004). "MPCS: Multidimensional Project Control System." *International Journal of Project Management*, 22(2), 109-118.

Rowings, James E., Nelson, Mark G., and Perry, Kimberly J., (1987). "Project Objective-Setting by Owners and Contractors." A report to the Construction Industry Institute.

Saaty, Thomas L., (1990). *The Analytic Hierarchy Process – Planning, Priority Setting, Resource Allocation*, RWS Publications, Pittsburgh.

Saaty, Thomas L., (1982). *Decision Making for Leader*, Lifetime Learning Publications, Belmont, CA.

Shields, David R., Tucker, Richard L., and Thomas, Stephen R., (2003). "Measurement of Construction Phase Success of Projects." *Proceedings of the Construction Research Congress*, ASCE.

Sims, Bradford L., and Anderson, Wayne, (2003). "Meeting Customer Expectations in the Construction Industry." *Cost Engineering*, 45(4), 30-32.

Sinthawanarong, K. P., and Emsley, M.W., (1998). "A Model for Contractors' On-site Performance Evaluation." *Proceedings of the First International Conference on New Information Technologies for Decision Making in Civil Engineering*, Montreal, 325-333.

Skibniewski, M. J., and Chao, L., (1992). "Evaluation of Advanced Construction Technology with AHP Method." *Journal of Construction Engineering and Management*, 118(3), 577-593.

Stewart, William R., and Horowitz, Evan R., (1991). "Environmental factor weighting at the federal energy regulatory commission." *Socio-Economic Planning Sciences*, 25(2), 123-132.

Tan, R. R., (1996). "Success criteria and success factors for external technology transfer projects." *Project Management Journal*, 27(2), 45-56.

Thamhain, Hans J., (2004). "Linkages of project environment to performance: lessons for team leadership." *International Journal of Project Management*, 22(7), 533-544.

Thomas, H.R. and Kramer, D.F., (1988). *The manual of construction productivity measurement and performance evaluation,* Construction Industry Institute, The Pennsylvania State University.

Turner, J. R., (1999). *The Handbook of Project-Based Management,* 2nd ed., McGraw-Hill Publishing, England.

Turner, J. R., (1993). *The Handbook of Project Based Management*, McGraw-Hill, New York.

Chapter 3

Forecasting Project Performance using Dynamic Markov Chains

3.1 Introduction

As mentioned in chapter one, it is important to not only control performance variances for actual project progress, but also to properly forecast the final project performance. At-completion performance variance can be predicted by comparing the target or baseline values with the most likely forecasted values. Such forecast is necessary for the project management team to decide if corrective action plans are required to minimize the predicted variances and the impact of these plans on the final performance. One of the most important requirements of a forecasting system is to provide early warning of performance overruns. Also, management does not trust a forecast that varies significantly from period to period and lacks stability. Thus there is a need for a system that is accurate, takes judgmental feedback, unbiased, timely, and stable. This chapter describes an approach to forecast the project performance at completion and at any other interim future point using to-date performance data and mathematical Markov-based rules. The proposed system is simple enough to be understood by qualified project management personnel and yet sophisticated enough to generate reliable and timely results.

Accurate project performance forecasts are difficult to produce when considering the impact of some factors such as material delays, scope deviation, poor productivity, unforeseen scope changes, and adverse weather conditions. Most of the current systems are not designed to incorporate this input in the form of a judgmental input from the user and consequently could lead to inaccurate results.

The issue of forecasting performance is of paramount importance to the project controls process in the construction industry. One of the most challenging tasks is predicting whether the project will be successful. The profitability of construction projects depends to a great degree on the ability of the construction organization to predict, well ahead of time, the project performance at completion *in all aspects* and take the necessary corrective action if needed. One way to effectively predict performance is to develop more reliable forecasting tools capable of accounting for the variability existing in construction operations. An integrated and comprehensive forecasting system, taking into consideration the probabilistic nature of construction performance, is an essential tool for any contracting organization that likes to stay competitive in the market. Variance data at any future time and at completion is very important to project management, and it is the objective of this work to develop a forecasting method that will determine this data as accurately and early as possible.

During the first quarter of a project it is particularly important to get warnings about significant overruns so that corrective action can be taken to prevent further decline. The earlier you realize that you have a problem on your project, the more prepared you are to mitigate that problem.

Although forecasting using indices is very common in the construction industry, the methods applied are normally based on the judgment of experts and/or linear trending approaches. Stochastic techniques such as Markov Chains are widely applied in many engineering and business domains but not in the field of performance forecasting of construction projects.

This research is based on the development of a forecasting methodology using the project objectives hierarchy established in chapter two and based on *Dynamic Markov Chains*. The end-users are construction organizations that need to predict future project performance. The model involves a lot of mathematical and statistical laws and requires huge data processing. But with the advances of the information technology, these difficult analytical processes are now considered simple.

This chapter reviews existing forecasting methods and demonstrates their pros and cons. Markov chains and processes are briefly introduced. An innovative stochastic forecasting model with its various extensions using *Dynamic Markov Chains* is developed. Advantages of the proposed model are also discussed. A conclusion is made at the end of this chapter.

3.2 Forecasting Methods: Literature Review

There is a significant literature on the topic of performance prediction. Major variances in one or more aspect of performance can significantly impact the overall project success and, in extreme cases, the realization of the project. Accurate and early prediction of the final status of a project could help management better influence the outcome by proposing and implementing more effective corrective action plans. Realizing the importance of forecasting in project management, many research efforts were made to develop methods to forecast the project status at completion. The majority of these methods were developed to predict the estimate at completion (EAC) and duration at completion. (EAC) is the best estimate of the total cost at the completion of project.

The methods found in the literature can be: (1) stochastic and probabilistic methods, (2) advanced computing methods (3) methods based on the earned value, (4) deterministic methods, (5) methods based on artificial intelligence and fuzzy logic, and (6) methods based on behavioral theories and judgmental forecasting. These methods will be briefly reviewed and discussed in the next section.

3.2.1 Stochastic and probabilistic methods

Lee (2005) introduced software, Stochastic Project Scheduling Simulation (SPSS), to predict the project completion probability, particularly at the time of bidding. The program incorporates the randomness and stochastic nature of the activities' durations. The study claims to be an improvement over PERT (which uses optimistic, likely, and pessimistic estimates), as it increases the prediction accuracy using simulation while it retains the CPM modeling environment. Although the system allows the user to enter diverse probability distribution functions (PDF's) it has major limitations: (1) the PDF's and activity times are assumed and are not based on historic data thus rendering the model generate unreliable results, and (2) the system does not allow data transfer from other commercial software.

Koksal and Arditi (2004) developed a statistical model that construction company managers can use to forecast whether their company is healthy, whether decline is setting in, or whether decline has reached an advanced stage. The early prediction of decline could assist executives to take corrective measures to prevent further decline. The company decline model assumed that the initial decline is caused by environmental, operational, and strategic factors.

Barraza et al. (2004) presented a new methodology, using the concept of stochastic S curves (SS), to forecast the at-completion project cost and schedule performance as well as at each 10% increment of project progress. A simulation approach was used for generating the stochastic S curves based on the variability in cost and duration of activities. Thus for each simulation iteration, one possible S-curve can be generated. This methodology provides an objective evaluation of project performance without the limitations of the deterministic approach. Distributions of possible values of at-completion budgeted cost (BAC) and at-completion schedule duration (DAC) can be analyzed at 100% progress. The study calculated the at-completion cost variation (ACV) as the difference between the expected budget at-completion (μ_{BAC}) and the expected estimate at-completion EAC (μ_{EAC}). Similarly, at-completion time variation (ATV) is evaluated as the difference between expected DAC (μ_{DAC}) and the expected time at-completion TAC (μ_{TAC}). The forecasted cost and time variances at-completion are shown in equations (3.1) and (3.2) respectively:

$$ACV = \mu_{BAC} - \mu_{EAC} \qquad \text{Equation (3.1)}$$

$$ATV = \mu_{DAC} - \mu_{TAC} \qquad \text{Equation (3.2)}$$

Using the above equations, positive at-completion variations represent favorable project performance. Using a probabilistic approach, the cost variance (CV) to-date is evaluated as the difference between expected BCWP (μ_{BCWP}) and (ACWP) as per Equation (3.3). Similarly, the time variation (TV) to-date is calculated as the difference between expected planned duration for work performed (μ_{PDWP}) and the elapsed time for work performed (ETWP) as shown in Equation (3.4).

$$CV = (\mu_{BCWP}) - ACWP \qquad \text{Equation (3.3)}$$

$$TV = (\mu_{PDWP}) - ETWP \qquad \text{Equation (3.4)}$$

Also, the model calculated (EAC) and (TAC) at the activity level using one of two methods proposed by the earned value techniques. Method (1) assumes that future performance will continue as originally planned as shown in Equations (3.5) & (3.6); and Method (2) assumes that future performance will equal to past performance using Equations (3.7) and (3.8).

$$EAC = ACWP + (BAC - BCWP) \qquad \text{Equation (3.5)}$$

$$TAC = ETWP + (DAC - PDWP) \qquad \text{Equation (3.6)}$$

$$EAC = BAC/CPI \qquad \text{Equation (3.7)}$$

$$TAC = DAC/TPI \qquad \text{Equation (3.8)}$$

Where,

TPI = PDWP/ETWP = Time Performance Index to-date.

Using a simulation approach, stochastic S-curves providing cost and time distributions can be obtained at any percent of work performed. Estimation of At-Completion performance variations is obtained to determine the need for corrective action. The proposed forecasting method uses methods based on the earned value methodology to account for performance correlations prior to performing simulation. This forecasting model, with the features mentioned above, could enhance the decision making process during construction execution.

Choi et al. (2003) compared the forecasting performance of simple and complicated methods used to forecast short-term construction volume. The authors explored the Mincer and Zarnowitz's method, Theil's *U* and *U2* statistic, Mean Square Forecasting Errors (MSFE), and turning point errors. The study did not discuss any method for forecasting construction performance. In conclusion, the authors recommended using a simple method in forecasting future construction volumes because it is comparable in performance to the complicated models.

Farghal and Everett (1997) used learning curves to predict the time or cost to complete the remaining cycles of the work in progress. A learning curve is generated by plotting the hours or cost required to complete one cycle as a function of the cycle number. The study used historical data for 60 construction activities from several published sources. Compared to other standard cost forecasting methods using linear projection of to-date actual costs (where estimate to complete is derived by multiplying the unit cost to-date by the remaining quantity), the proposed learning curve method is shown to be more accurate. The proposed method is only applicable to predict future performance of repetitive activities where learning effects are present.

3.2.2 Advanced Computing Methods

Isidore and Back (2002) integrated range estimating and probabilistic scheduling techniques through the development of a new procedure called the multiple simulation analysis technique (MSAT). It was developed to analytically quantify the complex interactions between the probabilistic cost and schedule data such that high confidence values for both parameters could be selected. The study indicated that choosing a schedule value with a high confidence level does not guarantee that the associated cost estimate, corresponding to the selected schedule value, will also have the same level of high confidence. (MSAT) combines discrete event simulation, regression analysis, and numerical analysis in order to model the relationship between the stochastic cost estimate and schedule data. The model will allow decision-makers to select highly probable schedule and cost estimates thus leading to accurate and reliable forecasts.

Al-Tabtabai (1998) developed a framework for a performance analysis and forecasting expert system. The system attempted to forecast construction performance in terms of cost and schedule using artificial neural networks and introduced the application of expert systems to represent the forecasting process of a construction project manager expert. The expert knowledge was acquired by interviewing a group of scheduling experts. The experts were asked to identify factors that could impact the cost and schedule performance at the completion of the project.

3.2.3 Earned-Value based Methods

The more commonly used deterministic forecasting techniques are based on the earned value concepts. As mentioned in Chapter 2, the Earned Value method can provide management with an early warning tool as early as the 15% completion stage on a project by allowing the project manager to forecast the project cost, commonly called the "Estimate At Completion (EAC)" and duration at completion (Fleming and Koppelman 2002). If the forecasted figures are not acceptable to management, corrective action can be taken at an early stage to improve the final results to meet expectations. These forecasting techniques, based on linear trend analysis, are very popular in the industry and are being used by many construction organizations. Also, the forecasting techniques employed in current project management systems, such as Primavera and Artimis, use historical performance to predict future outcomes. Most of these systems are based on the assumption that past performance is an indication of future performance. They apply simple regression analysis to forecast cost and schedule performance. A brief discussion of the earned-value based methods is provided below:

Seiler (1983) presented forecasting techniques for predicting cost and schedule performance based on the earned value concepts. The author calculated the estimate at completion assuming that the same level of cost efficiency experienced to-date would continue in the future. The study argues that at later stages of progress the future cost and schedule performance efficiency need to be modified based upon known conditions being experimented by the project. The author suggested modifying the CPI and/or the SPI by estimating a line of "best fit" through the monthly data points on the trend line. The "best fit" line can drawn by "free hand" or using linear regression.

Eldin and Hughes (1992) presented a detailed discussion of the use of unit costs to forecast the final cost. The study stated that an accurate forecast of final cost is based on applying unit costs to quantities using two approaches. The first approach is using the cumulative to-date unit cost [$(\$/Q)_a$] to estimate future unit costs. The second approach is assuming that the current-period unit cost [$(\$/Q)_{cp}$] is the best available estimate for future unit costs. The study argued that, unless there is a sound reason for selecting one over the other, both approached are equally accepted. Therefore, cost forecasts can be calculated by using one of the following equations:

$$C_1 = (Q)_b * (\$/Q)_a \qquad \text{Equation (3.9)}$$

$$C_2 = (Q)_a * (\$/Q)_a + (Q_b - Q_a) * (\$/Q)_{cp} \qquad \text{Equation (3.10)}$$

Where,

C1 & C2 are cost forecasts using the first and second approaches respectively.

$(Q)_a$ is the installed quantity, and

$(Q)_b$ is the current budgeted quantity.

Because equations (3.9) & (3.10) are likely to give different results, the study proposed to use the average of the two forecasts as the most likely figure. The total cost variance (V_S) can then be determined as the difference between the average forecasted cost and the total current budget $(\$)_b$ by the following equation:

$V_\$ = (\$)_b - (C_1 + C_2)/2$ Equation (3.11)

Christensen (1993) and Christensen et al. (1995) provided a comprehensive review of 25 studies that dealt with estimate at completion (EAC) formulas and models. The (EAC) formulas were classified into three categories: index, regression, and other (e.g. formulas based on heuristics). The generic index-based formula to calculate the estimate at completion (EAC) was proposed as follows:

$$EAC = ACWP_{to\_date} + \left(\frac{BAC - BCWP_{to\_date}}{index} \right) \qquad \text{Equation (3.12)}$$

Where,

ACWP = Actual Cost of Work Performed

BCWP = Budgeted Cost of Work Performed

BAC = Budget at Completion

The assumption implicit in the above equation is that the project's past cost and schedule performance is recurrent and reflective of future performance. The paper proposed that the performance *index* in the above equation is a combination of ACWP, BCWP, and BCWS and can take one of the following four functions:

1- *Index = CPI. Where CPI is the Cost Performance Index.*
2- *Index = SPI. Where SPI is the Schedule Performance Index.*
3- *Index = CPI*SPI*
4- *Index =* W_1**CPI +* W_2**SPI , where the weights (*W_1*&* W_2*) must add to unity.*

The study briefly reviewed comparative and non-comparative (EAC) research conducted over a period of sixteen years and made the following conclusions:

- The study showed that no one formula or model is always best. Attempting to generalize from a large and diverse set of EAC formulas is dangerous.
- The study did not establish the accuracy of regression-based models over index-based formulas. Additional research with regression models is needed.
- The study concluded that the accuracy of index-based formulas is a function of the system, and the stage and phase of the project. In addition, averaging over short periods (e.g., 3 months) is more accurate than averaging over longer periods (e.g., 6-12 months), especially during the mid stage of the project when costs are often accelerating.

Brown (1996) slightly modified the (EAC) equation (3.12) proposed in **Christensen (1993)** to correct for variance in future cost performance rates. The author proposed the following formula to determine the estimate at completion (EAC):

$$EAC = ACWP_{to\_date} + \left(\frac{BAC - BCWP_{to\_date}}{FCPI} \right) \qquad \text{Equation (3.13)}$$

Where,

FCPI = Forecasted Cost Performance Index for the remainder of the budgeted work to be performed.

Fleming and Koppelman (1994) proposed a constant budget model. The model assumes that all cost overruns can be absorbed through corrective action by the project end date and that the final cost will be equal to the original budget as represented by the following equation:

$$EAC = BAC \qquad \text{Equation (3.14)}$$

Where,

BAC = Budgeted cost at completion.

The major drawback is that the assumption implied by the model could apply to a very small number of projects and in most cases the actual cost at completion will differ from the budgeted cost.

Fleming and Koppelman (1994) proposed the schedule performance efficiency model that assumed that the forecasted final cost (EAC) is a function of both the Cost Performance Index (CPI), and the Schedule Performance Index (SPI) as described in the following equations:

$$EAC = \frac{BAC}{CPI \times SPI} \qquad \text{Equation (3.15)}$$

$$D = \frac{D_b}{CPI \times SPI} \qquad \text{Equation (3.16)}$$

Where,

D = forecasted duration at completion, and

D_b = planned project duration.

Research carried out by Zwikael et al. (2000) showed that this model is inferior to the model where EAC is function of the CPI only.

Shtub et al. (1994) developed the constant performance efficiency model, which assumed that the cumulative cost and schedule performance indices (CPI and SPI) remain unchanged or constant throughout the remaining project duration. This model proposes the following equations to measure the project cost and duration at completion:

$$EAC = \frac{BAC}{CPI} \qquad \text{Equation (3.17)}$$

$$D = \frac{D_b}{SPI} \qquad \text{Equation (3.18)}$$

Fleming and Koppelman (1995) and Zwikael et al. (2000) suggested that this model is better that the other earned-value based models.

Al-Tabtabai (1996) forecasted the performance at completion by considering eight influencing factors to impact the project performance index (*I*) as presented by the following equation:

$$I = 0.3f_1 + 0.26f_2 + 0.2f_3 + 0.15f_4 + 0.009f_5 + 0.17f_6 - 0.02f_7 + 0.15f_8 - 1.09 \qquad \text{Eq. (3.19)}$$

Where,

f_1 = Performance of management
f_2 = Cash flow situation
f_3 = Material and equipment availability
f_4 = Labor availability and productivity
f_5 = Weather and other environment influences
f_6 = Amount of rework, extra-work, and work difficulty.
f_7 = Percentage of work completed
f_8 = Past project's performance trend

Since the above equation contains many subjective factors, its accuracy is highly dependent on the quality of judgments and the ability to capture project specific data. This limitation can be overcome to a certain extent by selecting well-experienced professionals in the construction industry as domain experts for knowledge representation.

Robinson and Abuyuan (1996) proposed the "Scheduled Performance Estimators – SPEs) method to assess the project schedule status. This model defined the schedule performance index (SPR), the baseline average slope before report date (SBL), the actual average slope before report date (SA), the baseline average slope after the report date (MBL) by the following equations:

$$SPR = \frac{PERA}{PERBL} \qquad \text{Equation (3.20)}$$

$$SBL = \frac{PERBL}{report\ date} \qquad \text{Equation (3.21)}$$

$$SA = \frac{PERA}{report\ date} \qquad \text{Equation (3.22)}$$

$$MBL = \frac{PERAC\text{ - }PERBL}{TBL\text{ - }report\ date} \qquad \text{Equation (3.23)}$$

Where,

PERA = number of activities actually completed as of the report data date.

PERBL = number of activities planned to be completed as of the report data date.

PERAC = number of activities completed as planned at completion.

TBL = baseline completion date.

Using the above parameters, the model calculates the schedule variance at completion depending on how the project will proceed in the future. The major drawback of this model is assuming that all activities have equal weights, which is not the case in any construction project. To overcome this disadvantage, **Alshaibani (1999)** modified this method by assigning the activity duration as a weight to the SPR equation. The modified SPR is defined as follows:

$$SPR = \frac{\sum_{j=1}^{PERA} \frac{D_{b_j} \times PERA}{\sum_{j=1}^{n} D_{b_j}}}{\sum_{j=1}^{PERBL} \frac{D_{b_j} \times PERBL}{\sum_{j=1}^{m} D_{b_j}}} \qquad \text{Equation (3.24)}$$

Alshaibani (1999) modified equation (3.12) proposed by Christensen (1993) by adding to the performance index, a future improvement coefficient (α) that varies from 0 to 100. The developed equation to forecast the estimate at completion is as follows:

$$EAC = ACWP_{to\_date} + \left(\frac{BAC - BCWP_{to\_date}}{index} \right) \qquad \text{Equation (3.25)}$$

Where the *index* can take one of the following functions:

1- $Index = (\alpha\% + \text{CPI})$

2- $Index = (\alpha\% + \text{CPI})(\alpha\% + \text{SPI})$

Earned Value-based Methods to forecast the Cost at Completion

There are many formulas scattered in the earned value literature that are used to forecast the Estimate at Completion (EAC). The following is a brief description of some of the used forecasting methods:

- **A- 3 Period Average CPI**

This method calculates the (EAC) using a performance factor based on a three-period average of current cost performance. The following formula is used:

$$EAC = ACWP + \left(\frac{BAC - BCWP}{CPI_{3mo}} \right) \qquad \text{Equation (3.26)}$$

This approach assumes that the average cost performance of the last three periods (e.g., months) will continue through out the remaining project duration. Some practitioners compute the CPI using an average of 6 periods (months), others use the current period CPI.

- **B- Cumulative CPI**

This method calculates the (EAC) using the cumulative value of the Cost Performance Index. The following formula is used:

$$EAC = ACWP + \left(\frac{BAC - BCWP}{CPI_{cum}} \right) \qquad \text{Equation (3.27)}$$

This approach assumes that the average cost performance to-date will continue through out the remaining project duration.

- **C- CPI = 1 for Remaining Work**

This method assumes that "work from a particular point forward will progress at planned rates, whether or not those rates have prevailed to this point" (AACE 1992). It calculates the (EAC) using the same formula as in equation (3.27) but with a CPI value of 1. So *EAC* is the original budget plus the cost variance to-date (*CV*) and it is represented as follows:

$$EAC = ACWP + \left(\frac{BAC - BCWP}{1} \right) = BAC + CV \qquad \text{Equation (3.28)}$$

- **D- Cumulative weighted CPI and SPI**

This method calculates the (EAC) using a performance factor based on a weighted combination of the Cost and Schedule Performance Indices as per the following formula:

$$EAC = ACWP + \left(\frac{BAC - BCWP}{\alpha CPI_{cum} + \beta SPI_{cum}} \right) \qquad \text{Equation (3.29)}$$

This approach assumes that the cost at completion is a function of both the schedule and cost performances whose weights (α,β) are user-chosen and must sum up to unity.

- **E- Cumulative CPI * SPI**

This method calculates the (EAC) using a performance factor based on a combination of cost and schedule performance. It is calculated as follows:

$$EAC = ACWP + \left(\frac{BAC - BCWP}{CPI_{cum} * SPI_{cum}} \right) \qquad \text{Equation (3.30)}$$

Some practitioners compute the performance factor as $CPI_{6mo}*CPI_{6mo}$ (using an average of 6 periods months).

- **F- Linear Regression**

The goal of regression analysis is to achieve a description of relationships between variables which best fits the relationships established by sets of measured data. A linear line of regression is the straight line which best fits a set of data.

In our case, the linear regression formula is determined by deriving the equation of the straight line that best fits the plot of the cumulative values of *ACWP* vs. *BCWP*. The Estimate at Completion (EAC) is then obtained by substituting the Budget at Completion (BAC) into that formula.

Figure 3.1 shows a plot of ACWP vs. BCWP from the start of project till current data date, along with a "best-fit" straight line of slope "*m*". The straight line can then be used to plot the forecast of ACWP for any given BCWP.

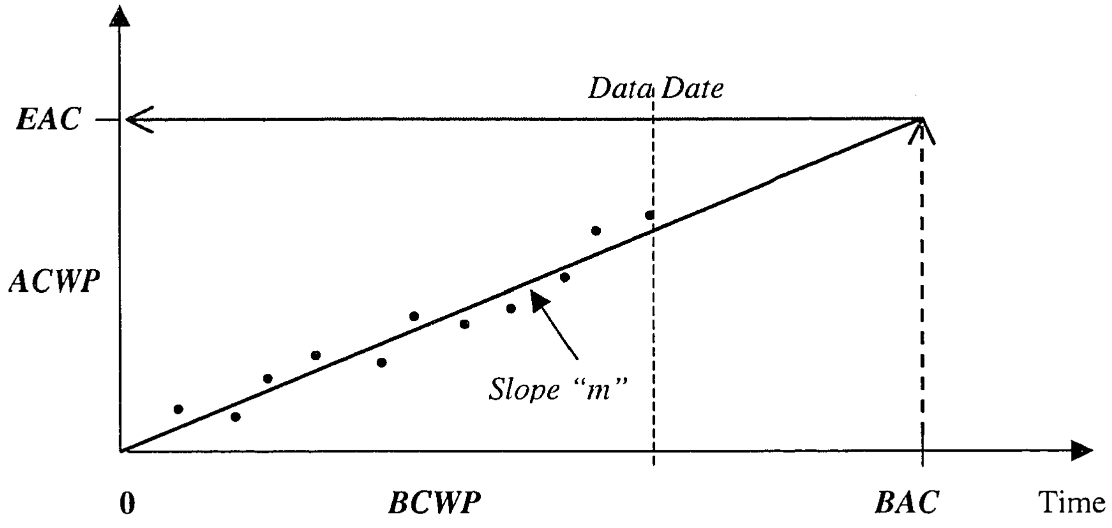


Figure 3. 1 Best-fit straight line to calculate the EAC

Based on the above trend line and assuming BCWP = ACWP = 0 at time 0, *EAC* can be expressed using linear regression by the following formula:

$$EAC = m * BAC \qquad \text{Equation (3.31)}$$

In all the above techniques, cost forecast projections follow linear profiles as per the conventional earned value concepts. Singh (1993) compared this conventional technique for calculating the estimate at completion (EAC) with a new technique that applies non-linear profiles to project cost forecasting using the beta distribution. The non-linear method gives differences of up to –5% for the studied projects.

3.2.4 Deterministic Methods

Forecasting performance values can be performed using two approaches: deterministic and probabilistic. The deterministic approach estimates cost and schedule using the most likely values, whereas the probabilistic approach assumes variability of cost and duration of activities. In spite of the presence of many probabilistic methods, deterministic methods are more commonly used by construction organizations because they are based on simpler models. Many of the deterministic forecasting methods use performance trend analysis. The following is a brief summary of the reviewed methods.

Teicholz (1993) proposed a method that uses the *sliding moving average* and to-date cost data to forecast the final cost of a construction project. The number of time periods used for the moving average varies depending on the stability of project performance (more periods are used if performance is variable). Hence the method is called the "sliding moving average" approach (SMA). The basic idea is that persistent trends in project productivity can be used for forecasting remaining work, while unstable trends cannot. Thus, a sufficient number of periods must be included in the moving average to produce a stable trend. The number of periods can range from a minimum of three periods to a maximum of the total periods to date. The proposed method was compared to two existing methods and was found to be superior in terms of accuracy, timeliness, and consistency. Method 1 extends to-date performance for the remainder of the project if the project is more than a specified % complete. Method 2 uses the moving average of the last k time periods (k >2) to forecast the remaining cost.

The limitation of this research is that the results were derived from the analysis of projects performed by a single construction company. The methods should be tested with data from other contractors before making a general conclusion. In addition, the proposed method forecasted cost only without considering other performance parameters or linking cost data to schedule data.

Wheelwright (1995) evaluated various subjective and deterministic mathematical methods and concluded that there is no single deterministic forecasting method that is accurate and superior for all projects and under all circumstances. However, the study stated that some simple techniques, such as the moving average, might produce better forecasts than complicated techniques.

Dawood and Molson (1997) developed specifications for a strategy that forecasts construction costs through integration of cost indices forecasts and construction plans. The forecasting module predicts the cost indices for six quarters ahead and uses various forecasting techniques like: Simple Moving Average, Single Exponential Smoothing, Exponential Smoothing and Decomposition Method. It was concluded that the

Decomposition technique has produced better results compared to other techniques and it is capable to handle judgmental feedback to tune the final forecasting figures. Cost forecasting in this research is limited to predicting future expenditures at early stages of project design and before construction starts.

3.2.5 Methods using Artificial Intelligence, Expert Systems and Fuzzy Logic

Nay and Logcher (1986) presented an artificial intelligence (AI) system that forecasts time and cost variances at the work package level. **Collopy and Armstrong (1992)** described an expert system rule-based forecasting model for combining time-series extrapolations. The model uses rules from domain experts to select from four extrapolation methods based on 18 features in the data. The authors suggest that this approach is particularly useful "in situations involving significant trends, low uncertainty, stability, and good domain expertise."

Fuzzy-based forecasting techniques use fuzzy data and fuzzy rules to predict the status of future performance. The following will briefly review related applications developed by Boussabine and Elhag (1999), Fayek (2000), Knight and Fayek (2002), and Li (2004).

Boussabine and Elhag (1999) developed a subjective model to predict cash flow at the project level. Statistical results from 30 case studies were used to develop the fuzzy membership functions for each evaluation period. Three linguistic terms: "Low", "Medium", and "High" were used and to describe the scope of each evaluation period. The current cash flow status was described in terms of "Pessimistic", "Moderately Optimistic", and "Optimistic".

Fayek (2000) proposed a reasoning framework for the prediction of design performance. Fourteen input factors that impact design performance and three output factors that measure design performance were listed. Each factor was further divided into sub-factors. A set of If-Then rules was developed and formed the basis of a fuzzy expert system that forecasted the performance of design.

Knight and Fayek (2002) proposed a fuzzy logic model to predict cost overruns/under runs in engineering design projects and consequently forecast profit. Fuzzy binary relation was used to model the relation between thirteen project characteristics and eight risk events on one hand, and the cost overruns resulting from any combination of project characteristics and risk events on the other hand. Ten degrees of forecasted cost performance were identified.

Li (2004) developed an indicator-based fuzzy forecasting method to forecast the project cost and duration at completion as well as at interim future points. The method utilized the fuzzy inference process and the principle of GMP (Generalized Modus Ponens) type reasoning. The model used thirteen terminal indicators as input variables to predict future cost values. Two performance indicators were utilized to predict the project duration of a control object. The model used a set of thirty-six fuzzy If-Then rules to predict cost and schedule and included a self-learning adjustment process to improve the accuracy of the predicted values. The developed system could generate reports at three levels: project, control-object, and individual resource.

Georgy et al. (2005) used neuro-fuzzy intelligent systems by integrating artificial neural networks and fuzzy control systems to predict the engineering design performance in industrial construction projects. Using actual project data, the authors developed linear regression models for the same performance scheme and compared the results between both techniques. The study proposed ten measures of engineering performance that cover the engineering, procurement, construction and commissioning phases. The study did not consider the impact of design on maintenance and operation. These performance measures are listed below:

Detailed Design Phase:

- Design rework (%)
- Design document release commitment
- Detailed design schedule delay (%)

- Detailed design cost overrun (%)

Procurement and Construction Phase:

- Fabrication and construction schedule delay due to design deficiencies (%)
- Fabrication and construction cost increase due to design deficiencies (%)
- Construction hours for design problem solving and field design (%)
- Estimated dollar savings due to constructability (%)

Start-up and Commissioning Phase:

- Startup schedule delay due to design deficiencies (%)
- Startup cost increase due to design deficiencies (%)

3.2.6 Methods based on Behavioral Theories and Judgmental Forecasting

Diekmann and Al-Tabtabai (1992) introduced the social-judgment theory (SJT) approach to forecast project performance. This new approach uses judgment, rather than purely mathematical methods, and is concerned with building a model of the cognitive system to predict the future based on a set of information (cues). The social-judgment method uses multiple regression to represent the person's judgment as the dependent variable and the values of the cues as the independent variables. This judgment (*J*), called a policy in SJT, is represented by the following equation:

$$J = w_1 x_1 + w_2 x_2 + \ldots + w_k x_k + c + e \qquad \text{Equation (3.32)}$$

Where,

J = judgment of an individual

x_k = cues used to make the judgment

w_k = weights for the cue variables

c = constant term for the individual

e = error term

The judgmental analysis was applied to the forecasting of project cost and schedule performance at the construction work package level (CWP's). Forecasts of judgments were developed for the following types of variances:

- Quantity-usage variance
- Labor-productivity variance
- Labor wage-rate variance
- Materials price-rate variance
- Equipment cost variance
- Work-package schedule variance

What differentiates this method from the earned-value based techniques is its way of predicting the future by not only considering the current status but also other factors that might impact the future outcomes. The major disadvantage is that it is heavily dependent on the judgment and expertise of the project managers. If the input information were not reliable, the model would not produce satisfactory results.

Hill (1970) introduced a set of judgmental forecasting techniques like the Delphi technique. The Delphi technique is a means for elicitation of opinion in order to obtain response from a group of experts. It uses the rule that "several heads are better than one".

The deficiencies in judgmental forecasting have been widely criticized. In most cases, such forecasting is carried out in a naïve fashion and the results are often quite unreliable.

3.2.7 Miscellaneous Methods

Patten (1987) developed a basic model for construction production forecasting using notions that are similar to the supply and demand concept that has been used in modeling the production inventory problem.

Khosrowshahi (1988) developed a mathematical model for use by the client and the contractor to forecast the project costs and revenue. The model is capable of generating a satisfactory forecast quickly and easily at any time of the project. While the model demands little input from the user, it does allow the user to develop a solution. The model parameters can be adapted, without modifying the structure of the mathematical expression, to meet the requirements of specific users with specific project characteristics.

Mazzini (1991) applied the Momentum Theory, an alternative approach to cost analysis founded on the dynamics of spending, for cost analysis, forecasting, and control. This new technique involves a multi-step process to transform historical data into the characteristic momentum patterns. The resulting patterns, and the future course of spending they produce, allow the cost analyst to accurately forecast the future.

3.2.8 Discussion

Forecasting has been and still considered a great challenge for effective project controls. To help practitioners better manage their construction projects, researchers have developed and presented various forecasting tools. Most of the reviewed papers based their forecasting methodologies on the "linear trend" concept. In addition, most of the methods forecasted the cost and schedule aspects and did not predict the overall project success. The majority of the earned-value based forecasting methods assumed that past performance would continue throughout the remaining duration of the project. These methods did not incorporate the impact of future corrective actions on future performance. Moreover, when there is a change in the project environment or in the organization, these methods may be of limited use. The method of Diekmann and Al-Tabtabai (1992) using the social judgment theory predicted future performance based on a set of cues, which were derived from human subjective judgment rather than objective mathematical methods. This method requires the input of highly experienced and knowledgeable project managers to produce satisfactory results. Fuzzy-based forecasting techniques are those methods where the status of future performance is derived from fuzzy data and fuzzy rules, similar to applications developed by Boussabine and Elhag (1999), Fayek (2000), and Knight and Fayek (2002). The parameters utilized by these methods are risk or success factors and are not directly related to the performance criteria.

The above review of the existing forecasting systems reveals that there is still a need for innovative research in the area of forecasting systems. This paper attempts to focus on forecasting construction performance.

The above literature review is not exhaustive, but it shows that while there are many studies on forecasting project cost and schedule, there is little on the methods available for forecasting all other aspects of performance like quality, safety, and team satisfaction. In practice, the most accurate approach is to periodically carry out objective and comprehensive estimate and schedule based on detailed quantities and unit rates of the remaining work. While this is the most accurate method, it is not easy to implement every period because it is time consuming and labor intensive especially when what-if scenarios are considered. For these reasons, this detailed approach is only done, at most, on a quarterly basis and/or when there are major and drastic changes to the scope of work. As a result, it is important that a contractor uses a relatively simple and less expensive method that can be implemented on a bi-weekly or monthly basis and provide management with early warning about potential performance variances.

3.2.9 Need for a probabilistic system

According to Willis (1987) a forecast can be based on past performance as long as the changes in the environment are steady. However, the construction industry is very dynamic and complex, and past performance is not always an accurate prediction of the future. There are many internal and external factors that can impact performance and thus, there is a need for a system to model the dynamic and probabilistic nature of construction performance. Given these conditions, forecasts must also incorporate, in one form or another, the expert or project manager judgment. This expertise and knowledge of the project's surrounding conditions must be modeled and incorporated into the forecasting system. A good forecasting method thus needs to include both historical trend data and reliable judgments based on construction experience and knowledge (Diekmann and Al-Tabtabai 1992). Neil (1987) recognized the imprecision of deterministic forecasting methods and recommended that no single deterministic method be used but rather many different methods providing a range of possibilities. Ward and Lithfield (1980) stated that it is important to recognize that projects are subject to continuous change, and hence a straight-line assumption is incorrect. The study also stated that using a forecast, based purely on past performance, is incomplete.

3.3 Probabilistic Forecasting of Project Performance using Markov Chains

Project performance can be impacted by many factors including current status and future corrective action plans. As a result, forecasting becomes a challenging task because planners have to understand and incorporate the influence of past performance and the impact of future plans on future performance. The following sections will present a forecasting model that project managers can use to predict future construction performance. The proposed model cannot produce reliable results without the user judgment, which is based on engineering knowledge and past experience.

To address the stochastic nature of performance, a probabilistic forecasting technique using Markov chains is proposed in this study. The developed model is based on the Integrated Project Evaluation Model (IPPM) presented in Chapter Two and attempts to predict at-completion project performance as well as at any interim point. It works on the assumption that the current cumulative actual progress is a good indication for future progress but is not the only factor that impacts future performance. To consider this correlation, a Markov chain is used to model future performance based on current performance. In addition, performance of construction projects is affected by many factors that are difficult to assess quantitatively. Thus a probabilistic approach that allows the user to logically incorporate the uncertainties is required. Instead of calculating a deterministic at-completion forecast, this study proposes a probabilistic analytical model based on Markov chains to estimate a probabilistic forecast.

According to Neil (1987), very few construction companies are comfortable with complex forecasting techniques. However, if contractors wish to improve the quality of performance prediction, they must implement methods that are consistent with the probabilistic nature of forecasting. Therefore, *Markov Chains* has great potential if used to forecast a more realistic evaluation of at-completion project performance by considering performance variability and a simple modification of the *Markovian property* that assumes transition probability to be constant or time invariant. This study presents the concepts of the methodology of probabilistic performance forecasting using *Dynamic Markov Chains* and describes the mathematical model. Since reporting and evaluating the performance of projects is carried out periodically, i.e. at specific periods in time, then it can be modeled as a discrete time stochastic process.

This chapter presents a mathematical model, based on *Markov Chains* that allows decision makers (project controls/project managers) to describe and predict the behavior of project performance based on the integrated project performance structure established in Chapter two. The model can predict the performance of every performance index as well as the overall project performance.

3.3.1 Introduction to Markov Processes and Chains

A Markov process is a mathematical model that is based on principles developed by the Russian probability theorist A. A. Markov. Markov processes provide a framework that allows the modeler to analyze the behavior of certain complex systems that evolve randomly over time. A *Markov Process* is a special type of discrete-time stochastic process whereby the probability of going from one *state* to another at time $t+1$ depends only on the *state* occupied at time t. This is called the *Markov property* and indicates that our ability to predict the state of a system for any $t>t'$ will not be enhanced by a knowledge of any values of the system states earlier that t' (Gillespie 1992). If the number of *states* is finite, the process is called a *Markov Chain*. Moreover, if the transition can occur only at discrete points in time, the process is a *Discrete Markov*

Chain. Refer to Gillespie (1992) for a detailed description of the Markovian decision process.

In general, a system can be modeled as a Markov process if it has the following four properties:

- **Finite states**: The dynamic behavior of a system can be described by a finite number of states.
- **Initial probability distribution**: Initial probabilities can be determined for the system.
- **Markov property**: This means that a transition to a new state depends only on the current state and not on past states.
- **Stationarity property:** This means that transition probability between any two states is constant or does not change over time.

It should be noted that the validity of any method using Markov chains depends on the extent to which the above-mentioned properties are met by the actual system under study. It is almost certain in every project that the probability of transition in construction performance is not constant through out the project duration and is a function of progress. Furthermore, external factors and economic trends may impact the transition probabilities and this violates the *Stationarity Property* of a Markov process. Being this is the case, Markov analysis is not appropriate to model the performance of construction projects. As a result, a *dynamic Markov Chain,* where transition probabilities vary in time, is presented to model performance forecasting.

Markov modeling has been applied in many diverse areas such as population dynamics, inventory management, maintenance and management of facilities and utilities, equipment maintenance, market share analysis, and economic trend analysis. To the best of the author's knowledge there has been no application of Markov theory in the area of construction performance planning and management. This study will investigate the implementation of *Discrete Dynamic Markov Chains* to forecasting project performance.

3.3.2 Discrete Dynamic Markov Chains

Markov processes have been utilized in many decision-making situations in various fields. However, this approach has one major drawback due to the stationarity property of Markov as mentioned above and which states that the transition probability does not change (remains stationary) over time. This time-homogeneous assumption is not valid in the case of project performance prediction because the transition probabilities are dynamic and either increase or decrease as a function of time. For example, the probability that the Cost Performance Index (CPI) goes from state C (within budget) to state F (poor performance) at the start of the project is higher than towards the end of the project. In this study, this problem is overcome by the use of *dynamic Markov processes* where the transition probability matrices vary with time. This modified approach is more flexible than the classical Markov process as will be explained later in this study.

3.3.3 Applications of Markov Chains in Construction Management

A review of the literature related to the application of Markov chains in construction and maintenance revealed that Markov models for infrastructure management (e.g. transportation systems, water and sewer pipe networks, etc.) are quite common. For example, the Markov chains have been widely used for modeling the performance of highway bridges. **Touran (1997)** used Markov chain to model the states of work and non-work for a tunnel-boring machine. **Guignier and Madanat (1999)** presented a Markov model for the optimization of maintenance and improvement of infrastructure network facilities through optimal allocation of budgets between the two activities. **Micevski et al. (2002)** presented a Markov-based forecasting model for the structural deterioration of storm water pipes. **Zayed et al. (2002a)** used regression, Markov chains, and non-linear programming to study the performance of bridge paint systems. Also **Zayed et al. (2002b)** carried out life cycle cost analysis using economic analysis, a deterministic method, and Markov process, a stochastic approach, to evaluate the alternative rehabilitation strategies for steel bridge paint systems. **Morcous et al. (2003)** developed a Markovian deterioration model for concrete bridge decks. **Abaza et al. (2004)** described a discrete-time Markovian model to predict the deterioration of pavements.

Project performance models using Markov chains were not found in the literature. With the successful application of the Markov chain theory in the domain of infrastructure management and decision modeling, this study will attempt to apply this theory to predict project performance. The next section will explain the application of Markov chains to the forecasting of performance of construction projects.

3.3.4 Forecasting Project Performance Model using Dynamic Markov Chains

The dynamic Markov model provides a sound conceptual model for the performance forecasting process. A major advantage of a Markov chain approach is its ability to explicitly represent probabilistic relationships between current and future performance data. As per the integrated evaluation model presented in Chapter 2, the overall project performance can occupy any of five possible states PI(t) at time t, (i.e. A(t), B(t), C(t), D(t), & F(t)). Assume that the 5x1 vector, p(t), represents the probability distribution over PI(t). In other words, this is the predictive distribution of project performance at time t. Generally, the specification of a predictive distribution for a stochastic process is quite complicated with PI(t) being a function of previous states PI(t-1), PI(t-2), etc. (Bunn 1982). A *Markov Process*, however, is a special type of stochastic process whereby PI (t) is a function only of the preceding state PI (t-1). Since the performance of a project next period depends only upon its state today, then project performance follows a *Markov process*. This assumption is somewhat true because the performance status to-date is cumulative and reflects the past performance.

Because the description of a Markov process depends essentially upon the transitions from states adjacent in time, i.e. from PI(t) to PI(t+1), the model of this stochastic process is frequently referred to as a *Markov Chain* (Bunn 1982). As mentioned above, the theory of Markov process is based on the "memoryless" assumption (Markov property), which means that the probability of future project performance depends only on the present performance and not any past states of performance. This concept is shown mathematically by the following equation:

$$P[(PI)_{t+1} = C_{t+1}/(PI)_{t+1} = C_t, (PI)_{t-1} = C_{t-1}, \ldots\ldots, (PI)_1 = C_1, (PI)_0 = C_0)] \qquad \text{Equation (3.33)}$$

$$= P[(PI)_{t+1} = C_{t+1}/(PI)_t = C_t]$$

Where;

C_{t+1} = Condition, or Project Performance at time t+1.

C_t = Condition, or Project Performance at time t.

$(PI)_{t+1}$ = Project Performance index at time t+1.

$(PI)_t$ = Project Performance index at time t.

To construct a project performance forecasting model, we need to know the initial state distribution PI(0) and the transition probability matrix.

The first step consists of dividing the planned project duration *T* into *n* equal time intervals. To illustrate the concept, the following model is based on twenty periods (1,...,20) but could be adjusted to any number of reporting periods.

3.3.5 Finite State Dynamic Markov Chain

To implement this Markov-based model for performance forecasting, the matrix states have to be defined. The project performance system can occupy five possible finite states as per the IPPM model proposed in Chapter 2. These discrete states/conditions that range from *A* (outstanding performance) to *F* (poor performance) are summarized in Table 3.1. This table is presented for illustration only and needs to be customized for each project.

Table 3. 1 Overall Project Performance States

State	Performance Rating	Index Range	Average (PI)
A	Outstanding	I > 1.15	1.2
B	Exceeds Target	1.05<I<= 1.15	1.1
C	Within Target	0.95<I<= 1.05	1.0
D	Below Target	0.85<I<= 0.95	0.9
F	Poor	I <= 0.85	0.8

In the above table, ***PI*** is the project performance index given by:

$$PI(t) = \sum_{i=1}^{8} W_i(t) * I_i(t) \qquad \text{Equation (3.34)}$$

Where,

$W_i(t)$ = Utility weight or the relative importance of the performance index (I_i) with respect to the overall project performance (PI) at time t of the project.

$I_i(t)$ = Normalized performance index at time t of the project.

Each of the eight performance indices can occupy one of the five states at any time "*t*". Table 3.2 shows the five states of cost performance. The use of a larger number of performance ratings will increase the computational overhead without adding value to the accuracy of the model. If the size of the transition probability matrices increases, the mathematical problem will increase. In addition, proper estimation of these large transition probability matrices requires a larger historical record of performance data.

Table 3. 2 Project Cost Performance Index (CPI) States

State	Performance Rating	Index Range	Average (CPI)
A	Outstanding	I > 1.15	1.2
B	Exceeds Target	1.05<I<= 1.15	1.1
C	Within Target	0.95<I<= 1.05	1.0
D	Below Target	0.85<I<= 0.95	0.9
F	Poor	I <= 0.85	0.8

3.3.6 Transition Probability Matrix

When a system undergoes a change, we say that the system makes a *transition*. In other words, the term "transition" is used when a system changes from state ***i*** to state ***j*** during two consecutive periods. The term "transition probability" expressed as P_{ij} denotes the probability of the system going from state ***i*** to state ***j***. An *NxN* matrix called the transition probability matrix ***P*** commonly represents these transition probabilities. In this study, there are five states associated with five possible conditions of project performance as shown in table 3.1. For a system with "N" possible states, the Transition Probability Matrix [P] for a one-period transition is represented in Figure 3.2.

$$[\mathbf{P}] = \begin{bmatrix} P_{11} & P_{12} & \ldots\ldots & P_{1N} \\ P_{21} & P_{22} & \ldots\ldots & P_{2N} \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ P_{N1} & P_{N2} & \ldots\ldots & P_{NN} \end{bmatrix}$$

Figure 3. 2 Transition Probability Matrix

Where,

P_{ij} =Transition probability of a system changing from state ***i*** at time ***t*** to state ***j*** at time ***t+1***. The index ***i*** is used for the initial state, and index ***j*** for the future state.

For example, P_{12} is the probability of a system changing from state *1* at time t to state *2* at time $t+1$.

Since the system has to occupy at any time t one of the states *(1,2,3,4,...,N)* it follows that:

$$\sum_{j=1}^{N} P_{ij} = 1 \quad \text{for } i = 1,2,3,\ldots\ldots,N \qquad \text{Equation (3.35)}$$

If the above approach is applied to the performance forecasting problem at hand we arrive at the probability transition matrix as shown in Figure 3.6.

$$[\mathbf{P}] = \begin{array}{c|ccccc} \text{State} & A & B & C & D & F \\ \hline A & P_{AA} & P_{AB} & P_{AC} & P_{AD} & P_{AF} \\ B & P_{BA} & P_{BB} & P_{BC} & P_{BD} & P_{BF} \\ C & P_{CA} & P_{CB} & P_{CC} & P_{CD} & P_{CF} \\ D & P_{DA} & P_{DB} & P_{DC} & P_{DD} & P_{DF} \\ F & P_{FA} & P_{FB} & P_{FC} & P_{FD} & P_{FF} \end{array}$$

Figure 3. 3 Probability Transition Matrix for project performance

Where,

P_{ij} =Transition probability of project performance index changing from state i at time t to state j at time $t+1$ *for* $i, j = A, B, C, D,$ *and* F.

For example, the notation P_{CB} is the probability of project performance index (cost, schedule, quality, etc.) changing from state ***C***, *within target*, at time t to state ***B***, *above target*, at time $t+1$. Similarly P_{CD} is the probability of a specific project performance index (cost, schedule, quality, etc.) changing from state *C*, *within target*, at time t to state ***D***, *below target*, at time $t+1$.

Since project performance with respect to any aspect (cost, safety, quality, etc) has to occupy at any time ***t*** one of the states ***(A, B, C, D, F),*** it follows that:

$$\sum_{j=A}^{F} P_{ij} = 1 \quad \text{For } i = A, B, C, D, \& F \qquad \text{Equation (3.36)}$$

Figure 3.4 shows the permissible state transitions from state A "outstanding performance" to the other states. Please note that the system can still occupy after transition its current state with a probability P_{AA} and that $\boldsymbol{P_{AA} + P_{AB} + P_{AC} + P_{AD} + P_{AF} = 1}$.

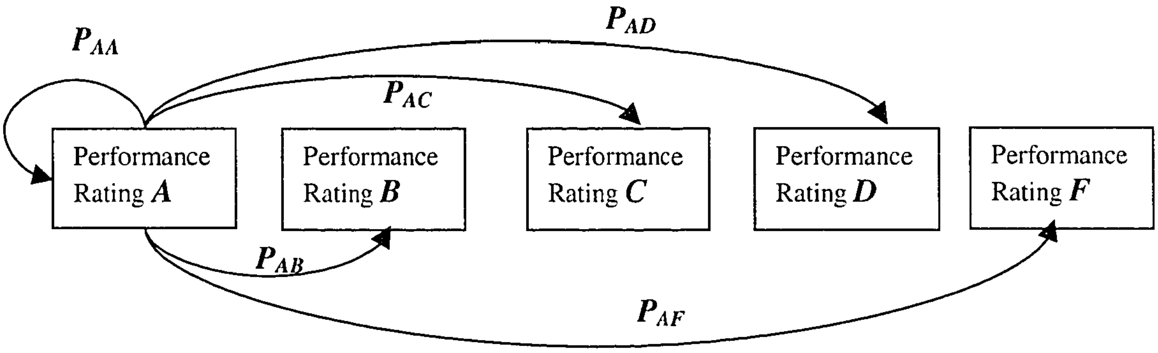


Figure 3. 4 Flowchart showing all the possible transitions from *state A*

Transition Matrices as a function of progress

It is assumed that the probability transition matrices for all the performance indices depend on the stage of the project. In the case of cost performance, the higher the progress of the project, the lower the probability of a transition from *within target* to the *poor* or *outstanding* states. This is due to the fact that towards the end of construction, most of the costs are committed and the influence on the cost at completion diminishes. Section 3.3.10 explains how to determine these transition matrices.

For each performance index, a methodology based on a *dynamic Markov chain* is used to model the way performance changes over the project duration.

3.3.7 Initial Probability Vector

A Markov Process begins at some initial time $t = 0$. In our case, the project performance in all areas (cost, schedule, quality, etc) at time $t = 1 = 0.05T$ is the initial state of the system as of the first reporting period. At time $t=0$, with no progress made or resources spent, the performance status cannot be defined.

$P(1)$ = Initial Probability Distribution for any performance index (CPI, SPI, PPI, etc)
= $[\, P_A(1),\ P_B(1), P_C(1), P_D(1), P_F(1)\,]$.

Where:

$P_A(1)$ = Probability of "***outstanding***" performance in the first reporting period.
$P_B(1)$ = Probability of "***above target***" performance in the first reporting period.
$P_C(1)$ = Probability of "***within target***" performance in the first reporting period.
$P_D(1)$ = Probability of "***below target***" performance in the first reporting period.
$P_F(1)$ = Probability of "***poor***" performance in the first reporting period.

The initial performance probability vector can be obtained from the company past records as will be explained in section 3.3.9. In summary, the project performance system can be modeled as a *Dynamic Markov Process* because it meets the following four properties:

- Finite states
- Initial probabilities
- Markov Property
- Dynamic Transition Probability Matrices

3.3.8 Reporting Period

Performance of construction projects should be evaluated on a periodic basis. Depending on the nature of the project, its duration, criticality and reporting requirements, reporting can be daily, weekly, bi-weekly, or monthly. Hourly and quarterly reporting are uncommon cases and usually used for shutdown projects and long term or stable projects respectively. This research is proposing 20 reporting periods throughout the project construction phase duration *(T)* at 5% time increments as shown in Table 3.3.

Table 3. 3 Table of Reporting Periods

Reporting Period (n)	**Reporting Time (t)**
1	0.05 T
2	0.10 T
3	0.15 T
4	0.20 T
5	0.25 T
6	0.30 T
7	0.35 T
8	0.40 T
9	0.45 T
10	0.50 T
11	0.55 T
12	0.60 T
13	0.65 T
14	0.70 T
15	0.75 T
16	0.80 T
17	0.85 T
18	0.90 T
19	0.95 T
20	1.00 T

3.3.9 Initial Probability Distribution

The initial probability distribution, at $t_1 = 0.05\ T$, can be derived based on the company record of similar past projects. For example, the initial probability vector for the Cost Performance Index (CPI) can be calculated as follows:

$$P_A(1) = \frac{\text{Number of projects whose CPI in the first period was outstanding (State A)}}{\text{Total Number of Projects}}$$

Equation (3.37)

$P_B(1)$, $P_C(1)$, $P_D(1)$, & $P_F(1)$ can be calculated in the same manner and the initial probability vector [$P_A(1)$, $P_B(1)$, $P_C(1)$, $P_D(1)$, $P_F(1)$] can be defined. We can extend the notation and define a state probability vector for the five proposed states for any performance index at any time ***t*** as follows:

$$P(t) = [\ P_A(t),\ P_B(t), P_C(t), P_D(t), P_F(t)\ ]$$

3.3.10 Estimation of Transition Probability Curve (TPC)

There are mainly three methods that can used to construct the transition probability curves. The first method is based on the experience and judgment of the construction management team. Using this approach (TPC's) can be constructed based solely on the past experience of the project manager and his assessment of current project conditions. The second method is to use the company past records of similar projects to calculate the transition probabilities. For example, if at a specific period of time *t* for a specific performance index and group of past identical projects, (N_D) represents the number of projects occupying performance state D (below target), and (N_C) represents the number of projects that occupied state C (within target) after one transition (or one reporting period), then the transition probability $\boldsymbol{P_{DC}}$ can be estimated using the following equation:

$$P_{DC} = \frac{N_C}{N_D} \qquad \text{Equation (3.38)}$$

The values of the (TPC's) obtained by Equation (3.38) could provide realistic curves if large number of past projects is used. The use of this method requires that construction organizations maintain performance records for a large number of projects at different performance states. The real challenge that faces the use of this approach is the lack of accurate performance records for all the past projects. Very few companies maintain a comprehensive and accurate performance database. In the absence of such information or when historical records are limited the following third method is proposed.

This study adopts a third method, which is a function of the progress curves of the project under consideration. This method assumes that the transition probability curve for any performance index is a function of the project S-Curve by *revenue*, *cost* or *man-hours*. Figure 3.5 shows a typical s-curve by cost. This is due to the fact that the probability of change in the cumulative index value is proportional to the rate of change in the corresponding S-Curve. Thus a typical probability curve, as a function of time, can be represented for any transition probability, as a third degree equation of the form:

$$P(t) = f(at^3 + bt^2 + ct + d) \quad for \quad 0.1T < t < 0.95T \quad or\ 2 < n < 19 \qquad \text{Equation (3.39)}$$

For example, the transition probability curve for cell P_{CC} of the cost performance index (CPI) can be represented as a function of time as follows:

$$P_{CC}(t) = f(at^3 + bt^2 + ct + d) \quad for \quad 0.1T < t < 0.95T \quad or\ 2 < n < 19 \qquad \text{Equation (3.40)}$$

Where,

T = total project duration and n is the reporting period number.

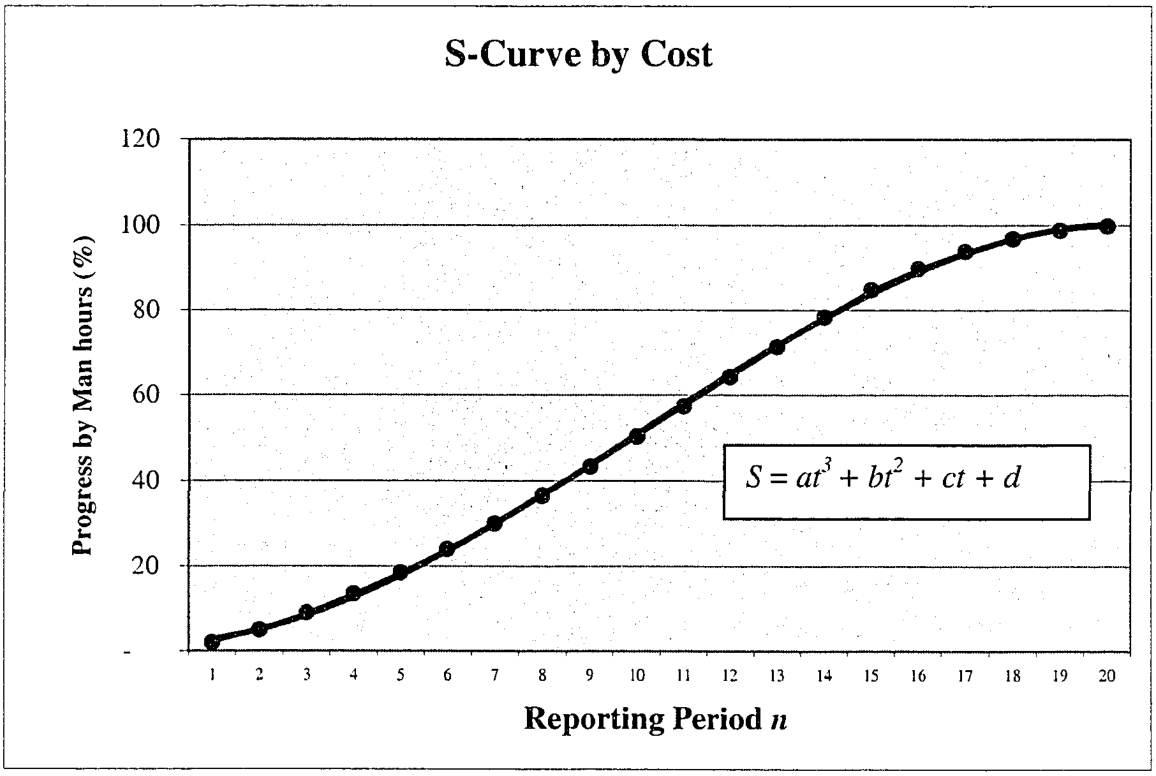


Figure 3. 5 Planned S-Curve by Cost

The constants a, b, & c of Equation (3.40) are obtained from the scheduled cost S-curve for the project under consideration using the defined scope of work. Table 3.4 shows the relation between the eight performance indices and the 3 types of S-curves.

Table 3. 4 Indices and associated S-Curves

Index	**Planned S-Curve**
CPI	By Cost
SPI	By Man Hours
BPI	By Revenue
PPI	By Revenue
SFI	By Man Hours
QPI	By Man Hours
TSI	By Man Hours
CSI	By Man Hours

Once the transition probability matrix is determined, the prediction of future performance by Markov chains becomes a matter of matrix multiplication. It should be noted that each value of the transition probability matrix is defined as the probability of *performance index I* transitioning from state ***i*** to state ***j*** in one time (reporting) period.

3.3.11 Boundary Conditions

The boundary conditions, at $t_2 = 0.1\ T$, and $t_{20} = 1.0\ T$ are calculated based on the company past records for an identical set of projects executed under similar conditions. For example, the P_{CC} value at $t_2 = 0.1\ T$, and $t_{20} = 1.0\ T$, for the Cost Performance Index (CPI) and can be calculated as follows:

$P_{CC}(t_2) = CC_2/TN$ Equation (3.41)

$P_{CC}(t_{20}) = CC_{20}/TN$ Equation (3.42)

Where,

CC_2 = Number of projects whose CPI at ***t_1=0.05T (n=1)*** was ***within target*** (State C) and continued to be ***within target*** (State C) at ***t_2=0.1T (n=2).***

CC_{20} = Number of projects whose CPI at ***t_{19}=0.95T (n=19)*** was ***within target*** (State C) and continued to be ***within target*** (State C) at ***t_{20}=1.0T (n=20).***

TN = Total Number of Projects whose CPI at t_1/t_{19} was *within target.*

Hence we can generalize and write:

$$P_{CC}(t) = \begin{cases} P_{CC}(t_2) - [P_{CC}(t_2) - P_{CC}(t_{20})]*[\ at^3 + bt^2 + ct + d\ ] & for \quad 2 < t < 20 \\ CC_2/TN & for \quad t = 2 \\ CC_{20}/TN & for \quad t = 20 \end{cases}$$

Equation (3.43)

Based on above, the transition probability function P(t) for any transition from state ***i*** to state ***j*** can be expressed as:

$$P_{ij}(t) = P_{ij}(t_2) - [P_{ij}(t_2) - P_{ij}(t_{20})]*[\, at^3 + bt^2 + ct + d\,] \qquad for \quad 2 < t < 20$$

$For\ i, j = A, B, C, D, \&\ F.$ Equation (3.44)

Where $at^3 + bt^2 + ct + d$ is the equation of the planned s-curve by cost. The same approach can be applied to the other performance indices to generate the probability distribution curve, initial probability vector and boundary conditions.

3.3.12 Probability of Future States of Performance

The state probability vector at any time t is given by:

$P(t) = [\, P_A(t),\ P_B(t), P_C(t), P_D(t), P_F(t)\,]$

The state probability vector at time $t+1$ is given by:

$P(t+1) = [\, P_A(t+1),\ P_B(t+1), P_C(t+1), P_D(t+1), P_F(t+1)\,]$ Equation (3.45)

But $P(t+1) = P(t) * [\, P\,]^{t+1}$ Equation (3.46)

In Equation (3.46), $[\, P\,]^{t+1}$ is the probability transition matrix at $(t+1)$ as represented in Figure 3.7.

$$[\mathbf{P}]^{t+1} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ F \end{array} \begin{array}{ccccc} A & B & C & D & F \\ \end{array}$$

$$[\mathbf{P}]^{t+1} = \begin{array}{c|ccccc|} & A & B & C & D & F \\ \hline A & P_{AA}(t+1) & \dots & \dots & \dots & P_{AF}(t+1) \\ B & \dots & \dots & \dots & \dots & \dots \\ C & \dots & \dots & \dots & \dots & \dots \\ D & \dots & \dots & \dots & \dots & \dots \\ F & P_{FA}(t+1) & \dots & \dots & \dots & P_{FF}(t+1) \end{array}$$

Figure 3. 6 Probability Transition Matrix at time $(t+1)$

Note that: $\sum_{j=A}^{F} P_{ij}(t) = 1$ for $i = A, B, C, D, \&\ F$

Using Equation (3.46) we can write:

$P_A(t+1)$= Probability of ***outstanding*** performance at $t+1$

$$=[P_A(t)*P_{AA}(t+1)+P_B(t)*P_{BA}(t+1)+P_C(t)* P_{CA}(t+1)+P_D(t)*P_{DA}(t+1)+P_F(t)*P_{FA}(t+1)\,]$$

$$=[P_A(t),\ P_B(t),\ P_C(t),\ P_D(t),\ P_F(t)\,] \text{ x } \begin{bmatrix} P_{AA}(t+1) \\ P_{BA}(t+1) \\ P_{CA}(t+1) \\ P_{DA}(t+1) \\ P_{FA}(t+1) \end{bmatrix} \qquad \text{Equation (3.47)}$$

$P_B(t+1)$= Probability of ***above target*** performance at $t+1$

$$=[P_A(t)*P_{AB}(t+1)+P_B(t)*P_{BB}(t+1)+P_C(t)* P_{CB}(t+1)+P_D(t)*P_{DB}(t+1)+P_F(t)*P_{FB}(t+1)\,]$$

$$=[P_A(t),\ P_B(t),\ P_C(t),\ P_D(t),\ P_F(t)\,] \text{ x } \begin{bmatrix} P_{AB}(t+1) \\ P_{BB}(t+1) \\ P_{CB}(t+1) \\ P_{DB}(t+1) \\ P_{FB}(t+1) \end{bmatrix} \qquad \text{Equation (3.48)}$$

$P_C(t+1)$= Probability of ***within target*** performance at $t+1$

$$=[P_A(t)*P_{AC}(t+1)+P_B(t)*P_{BC}(t+1)+P_C(t)* P_{CC}(t+1)+P_D(t)*P_{DC}(t+1)+P_F(t)*P_{FC}(t+1)\,]$$

$$=[P_A(t),\ P_B(t),\ P_C(t),\ P_D(t),\ P_F(t)\,] \text{ x } \begin{bmatrix} P_{AC}(t+1) \\ P_{BC}(t+1) \\ P_{CC}(t+1) \\ P_{DC}(t+1) \\ P_{FC}(t+1) \end{bmatrix} \qquad \text{Equation (3.49)}$$

$P_D(t+1)$= Probability of ***below target*** performance at $t+1$

$=[P_A(t)*P_{AD}(t+1)+P_B(t)*P_{BD}(t+1)+P_C(t)*P_{CD}(t+1)+P_D(t)*P_{DD}(t+1)+P_F(t)*P_{FD}(t+1)\,]$

$$=[P_A(t),\ P_B(t),\ P_C(t),\ P_D(t),\ P_F(t)\,] \text{ x } \begin{bmatrix} P_{AD}(t+1) \\ P_{BD}(t+1) \\ P_{CD}(t+1) \\ P_{DD}(t+1) \\ P_{FD}(t+1) \end{bmatrix} \qquad \text{Equation (3.50)}$$

$P_F(t+1)$= Probability of ***poor*** performance at $t+1$

$=[P_A(t)*P_{AF}(t+1)+P_B(t)*P_{BF}(t+1)+P_C(t)*\ P_{CF}(t+1)+P_D(t)*P_{DF}(t+1)+P_F(t)*P_{FF}(t+1)\,]$

$$=[P_A(t),\ P_B(t),\ P_C(t),\ P_D(t),\ P_F(t)\,] \text{ x } \begin{bmatrix} P_{AF}(t+1) \\ P_{BF}(t+1) \\ P_{CF}(t+1) \\ P_{DF}(t+1) \\ P_{FF}(t+1) \end{bmatrix} \qquad \text{Equation (3.51)}$$

The above can be written as follows:

$$P_A(t+1)= \sum_{S=A}^{F} P_S(t)*P_{SA}(t+1) \qquad \text{Equation (3.52)}$$

$$P_B(t+1)= \sum_{S=A}^{F} P_S(t)*P_{SB}(t+1) \qquad \text{Equation (3.53)}$$

$$P_C(t+1)= \sum_{S=A}^{F} P_S(t)*P_{SC}(t+1) \qquad \text{Equation (3.54)}$$

$$P_D(t+1)= \sum_{S=A}^{F} P_S(t)*P_{SD}(t+1) \qquad \text{Equation (3.55)}$$

$$P_F(t+1)= \sum_{S=A}^{F} P_S(t)*P_{SF}(t+1) \qquad \text{Equation (3.56)}$$

Where:

$P_S(t)$ = Probability of "S" performance at time t = $[P_A(t),\ P_B(t),\ P_C(t),\ P_D(t),\ P_F(t)\,]$.

3.3.13 Forecasting of Cost Performance

Based on above, knowing the present performance (or initial state), the forecasted cost performance index as at time *t* can be calculated as:

$$CPI(t) = \sum_{S=A}^{F} Ps(t) * CPIs$$

$$= P_A(t) * CPI_A + P_B(t) * CPI_B + P_C(t) * CPI_C + P_D(t) * CPI_D + P_F(t) * CPI_F$$

$$= P_A(t) * 1.2 + P_B(t) * 1.1 + P_C(t) * 1.0 + P_D(t) * 0.9 + P_F(t) * 0.8$$

Equation (3.57)

Where $CPI_{A,,}$ $CPI_{B,}$ $CPI_{C,}$ $CPI_{D,}$ & CPI_F are the average CPI values for outstanding, above target, within target, below target, and poor performance states respectively as proposed in Table 3.1. It should be emphasized that each project can use different average index values that reflect the project controls philosophy of the company and the specific conditions of the project.

The forecasted index indicates the level of cost efficiency but can't tell the magnitude of loss or gain. The degree of overrun or under-run of the project total cost at time "*t*" versus the total current budget at time "*t*" is defined by the cost variance $C_v(t)$ that can be expressed as:

$$C_v(t) = BC(t) - EAC(t) = BC(t) - \left(\frac{BCWP(t)}{CPI(t)}\right)$$ Equation (3.58)

Where,

$C_v(t)$ = Total Project Cost Variance as of time period "*t*".

$BC(t)$ = Total Current Budgeted Cost as of time period "*t*".

$EAC(t)$ = Total Estimate at Completion Cost as of time period "*t*", and

$BCWP(t)$ = Total Budgeted Cost of Work Performed as of time period "*t*".

At the end of the project, the cost variance at completion is calculated as per Equation (3.58) where $t = 20$.

Variance Convention

This study adopts the convention of variance = budget – actual as a general rule for all the performance indices. For example, in the case of cost, variance is equal to the budgeted cost less the actual cost. This is the most common convention used in cost engineering, which means that negative cost variances indicate overruns, while positive variances indicate cost savings. Variance data at any future time and at completion is very important to project management, and it is the objective of this work to develop a forecasting method that will determine this data as accurately and as early as possible.

3.3.14 Forecasting Overall Project Performance

In the same manner, the other performance indices can be forecasted at any future time *t* as follows:

$SPI_t = \sum_{S=A}^{F} Ps(t) * SPIs$ = Forecasted Schedule Performance Index at time t. Eq. (3.59)

$BPI_t = \sum_{S=A}^{F} Ps(t) * BPIs$ = Forecasted Billing Performance Index at time t. Eq. (3.60)

$PPI_t = \sum_{S=A}^{F} Ps(t) * PPIs$ = Forecasted Profitability Performance Index at time t. Eq. (3.61)

$SFI_t = \sum_{S=A}^{F} Ps(t) * SFIs$ = Forecasted Safety Performance Index at time t. Eq. (3.62)

$QPI_t = \sum_{S=A}^{F} Ps(t) * QPIs$ = Forecasted Quality Performance Index at time t. Eq. (3.63)

$TSI_t = \sum_{S=A}^{F} Ps(t) * TSIs$ = Forecasted Team Satisfaction Performance Index at t. Eq. (3.64)

$CSI_t = \sum_{S=A}^{F} Ps(t) * CSIs$ = Forecasted Client Satisfaction Performance Index at t. Eq. (3.65)

Forecasting the Project Performance Index (PI)

Based on above, the forecasted project performance index (PI) at any future time ***t*** can be expressed as in Equation (3.66):

$$\begin{aligned} PI(t) = {} & w_{CPI}(t)\sum_{S=A}^{F} Ps(t) * CPIs + w_{SPI}(t)\sum_{S=A}^{F} Ps(t) * SPIs + w_{BPI}(t)\sum_{S=A}^{F} Ps(t) * BPIs \\ & + w_{PPI}(t)\sum_{S=A}^{F} Ps(t) * PPIs + w_{SFI}(t)\sum_{S=A}^{F} Ps(t) * SFIs + w_{QPI}(t)\sum_{S=A}^{F} Ps(t) * QPIs + \\ & w_{TSI}(t)\sum_{S=A}^{F} Ps(t) * TSIs + w_{CSI}(t)\sum_{S=A}^{F} Ps(t) * CSIs \end{aligned}$$

Equation (3.66)

The *w(t)'s* in the above equation are the relative importance of the indices at time *t* with respect to PI as derived by the AHP method proposed in Chapter Two. It should be noted that the weights are not constant in most cases but vary over the project life cycle as explained earlier.

This Markovian model provides an adequate mechanism for predicting future performance of construction projects. The Markov process imposes a systematic approach on the forecasting process. It should be emphasized that the input to the model should be made by experienced users to reflect the real project conditions in order to obtain reliable forecasts.

3.4 Model Extensions

3.4.1 Update of Transition Probability Curves

An effective forecasting method must reflect, in addition to to-date performance, future anticipated changes in scope of work and other additional project-related data. Additional data available to the project team may include the following:

- Trend information,
- Changes in fabrication and sub-contract costs,

- Expected changes in labor productivity and/or labor unit rates,
- Stage of construction,
- Escalation of material prices,
- Undocumented or missed scope changes,
- Work process changes,
- Future requirements by client,
- Insight into resolved technical problems,
- Insight into future safety and quality problems,
- Insight into future cash-flow problems,
- Uncertainty of future events like labor strikes and adverse weather conditions.

In addition to above items that might lead to cost variations, the knowledge of a skilled project manager and his experience with the project's conditions is a vital resource and need to be incorporated into the forecasting model. The valuable project's specific knowledge obtained through continuous monitoring and analysis of the project environment and observations of the external factors need to be fed into the system.

Access to all the above additional data may cause the decision maker to reflect this input by modifying or updating the probability transition curves. This adjustment is required for each performance index and is implemented as follows:

The ***original*** transition probability function $P(t)$ is given by:

$$P_{ij}(t) = P_{ij}(t_2) - [P_{ij}(t_2) - P_{ij}(t_{20})] * [\, at^3 + bt^2 + ct + d \,] \text{ for } 2 < t < 20 \qquad \text{Equation. (3.67)}$$

Assuming that the data date is t_{dd}, then the ***revised*** transition probability value from performance state "*i*" to state "*j*" for $t > t_{dd}$, $P'_{ij}(t)$ is determined as:

$$P'_{ij}(t) = P'_{ij}(t_{dd}+1) - [P'_{ij}(t_{dd}+1) - P'_{ij}(t_{20})] * [a't^3 + b't^2 + c't + d'] \quad \text{for } t_{dd}+1 < t < 20$$

Equation (3.68)

Where:

$P'_{ij}(t_{dd}+1)$ = Revised Transition Probability from performance state "i" to state "j" at data date time $t_{dd}+1$. It could be determined by the user or decision maker based on the latest project information. The following equation is proposed to calculate $P'_{ij}(t_{dd}+1)$.

$P'_{ij}(t_{dd}+1) = P_{ij}(t_{dd}+1) * F_n$ subject to : $0 < P'_{ij}(t_{dd}+1) < 1$ Equation (3.69)

$P'_{ij}(t_{20})$ is the Revised Transition Probability from performance state "i" to state "j" at t = 1.0T (t_{20} is the last project reporting time). The decision maker based on the latest project information forecasts the revised probability. The parameters *a', b', c', & d'* are obtained from the revised forecasted S-curve updated at $t = t_{dd}$. Table 3.5 shows a list of proposed values for F. The following equation is proposed to calculate $P'_{ij}(t_{20})$.

$P'_{ij}(t_{20}) = P_{ij}(t_{20}) * F_n$ subject to : $0 < P'_{ij}(t_{20}) < 1$ Equation (3.70)

Table 3. 5 Modification Factors

Project Conditions	**Modification Factor F_n**	**Factor Range**
Much Favorable	F_1	1.1 – 1.2
Favorable	F_2	1.0 – 1.1
Less Favorable	F_3	0.9 – 1.0
Much less Favorable	F_4	0.8 – 0.9

The revised Transition Probability Curve is shown in Figure 3.8.

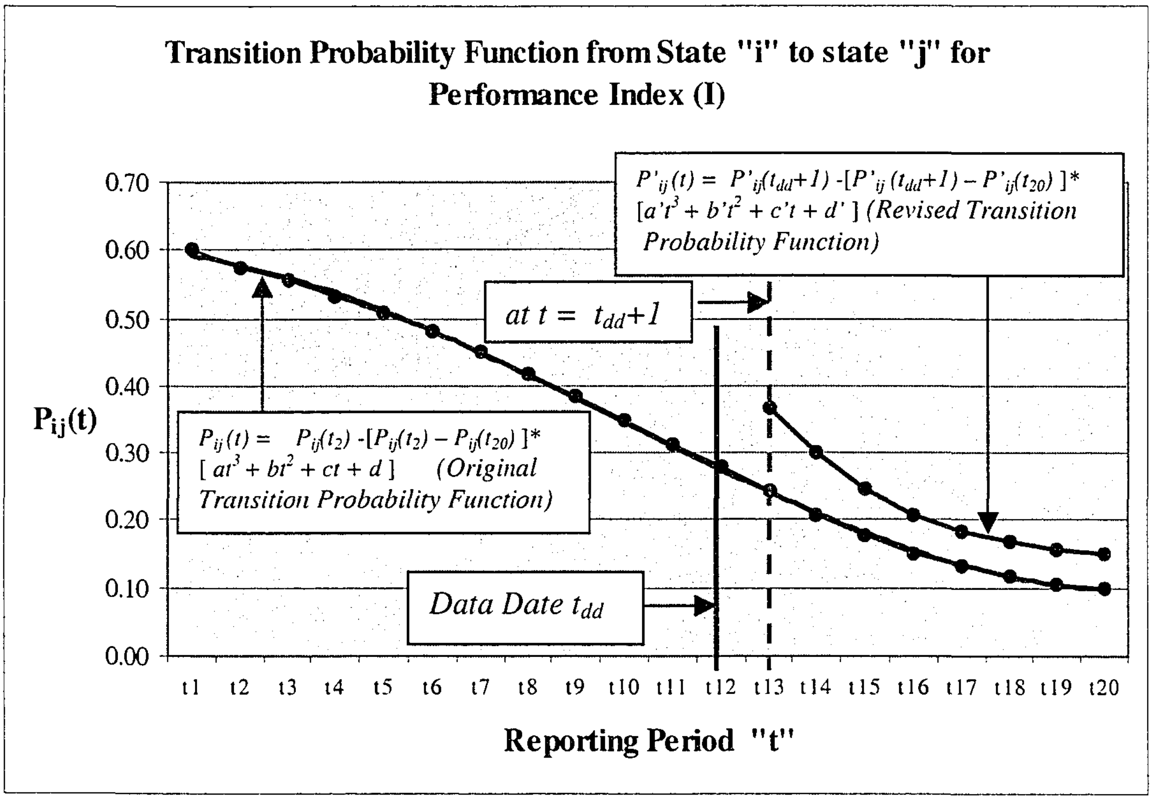


Figure 3. 7 Original and revised Transition Probability Functions

Update of Transition Probability Curves due to Corrective Action

The transition probability matrices need to be updated for each corrective action plan proposed. A systematic procedure of updating these matrices is demonstrated in Chapter Five as part of the performance optimization process.

3.4.2 First Passage Probabilities

In the previous section, we developed a mathematical expression for the probability $p^{(n)}_{ij}$ that a project performance will move from state "*i*" to state "*j*" after "*n*" transitions or "*n*" reporting periods. But this does not provide us any information about whether the project performance entered state "*j*" at any time before the "*n*" reporting period. To determine the probability that the project performance leaves state "*i*" and enters state "*j*" for the first time after "*n*" reporting periods, we have to calculate what we call the **first passage probability** $f^{(n)}_{ij}$ (Gillespie 1992) as given by Equation (3.71).

$$f^{(n)}_{ij} = p^{(n)}_{ij} - \sum_{k=1}^{n-1} f^{(k)}_{ij}\, p^{(n-k)}_{jj} \qquad \text{Equation (3.71)}$$

The first probability transition matrix at the n^{th} reporting period $[\mathrm{F}]^{\mathrm{n}}$ can be expressed as follows:

$$[\mathrm{F}]^{\mathrm{n}} = \begin{array}{c|ccccc|} \text{State} & A & B & C & D & F \\ A & f_{AA} & f_{AB} & f_{AC} & f_{AD} & f_{AF} \\ B & f_{BA} & f_{BB} & f_{BC} & f_{BD} & f_{BF} \\ C & f_{CA} & f_{CB} & f_{CC} & f_{CD} & f_{CF} \\ D & f_{DA} & f_{DB} & f_{DC} & f_{DD} & f_{DF} \\ F & f_{FA} & f_{FB} & f_{FC} & f_{FD} & f_{FF} \end{array}$$

Figure 3. 8 First Probability Transition Matrix

For example, $f^{(n)}_{CA}$ is the probability that project performance leaves state "*C*", *within target,* and enters state "A", *outstanding performance*, for the first time after "*n*" reporting periods. If $f^{(4)}_{CA} = 0.2$, then the probability that the project performance in the *4th* reporting period will be *outstanding* for the *first time,* given that it is currently *within target,* is 20%. The significance of the first passage probability is its ability to forecast the project performance status when it occurs for the first time.

3.4.3 Expected First Passage Time

The **first passage time** *(T_{ij})* of changing from performance condition "*i*" to "*j*" is the number of periods made by a Markov process as it goes from state"*i*" to state "*j*" for the first time. In other words, it is the time of first arrival in another specified state (Gillespie 1992).

If the Markov process is not certain to ever reach state *"j"*, then we can write:

$$\sum_{n=1}^{N} f^{(n)}{}_{ij} < 1 \qquad \text{Equation (3.72)}$$

Otherwise, the $f^{(n)}{}_{ij}$ are the probability distribution for the first passage times *Tij*, and

$$\sum_{n=1}^{N} f^{(n)}{}_{ij} = 1 \qquad \text{Equation (3.73)}$$

Where

N = Total number of reporting periods for the project, proposed in this research to be 20.

"i" & *"j"* = A, B, C, D, & F , or the project performance states.

We can then express the expected first passage times, $E(T_{ij})$, from state "*i*" to state "*j*" as:

$$E(T_{ij}) = \sum_{n=1}^{N} nf^{(n)}{}_{ij} = f^{1)}{}_{ij} + 2*f^{2)}{}_{ij} + 3*f^{3)}{}_{ij} + \ldots\ldots\ldots\ldots + 20*f^{20)}{}_{ij} \qquad \text{Equation (3.74)}$$

If $i = j$, then $E(T_{ii})$ is the expected recurrence time.

Using the above equations, the decision maker could have answers to the following questions that can help him better forecast and manage the project performance.

- How many reporting periods (week, month) might it take for a project with *poor performance* now to become *within target*?
- After how many reporting periods on the average will above target performance condition again be above target, after possibly going to other performance states?

3.4.4 The Forecasting Model and Time Variance

Although schedule variance (SV) is defined in this study in terms of cost ($'s or man hours), it is helpful to know the deviation in time (time variance) between actual progress and scheduled progress especially when SV is expressed in monetary units. This time variance (TV) need to be calculated to-date and at project completion. The following section will explain the time variance idea and how it is determined using the ***first passage time*** (T_{ij}) concept of the proposed Markov-based forecasting model.

Time Variance To-Date

If the time variance to date (TV_{dd}) is expressed in number of reporting periods and is defined as the difference between the time duration corresponding to the percentage of earned progress (T_e) (or the date at which the BCWS is equal to the BCWP) and the actual elapsed duration (T_a), then TV can be expressed as follows:

$$TV_{dd} = T_e - T_a \qquad \text{Equation (3.75)}$$

The concept of TV is illustrated in Figure 3.10, which shows that the time variance is also the difference in "time" between the BCWS and BCWP. It is obvious from the figure that if the time planned to do the present earned value is greater than the actual elapsed time, TV is positive and the project is ahead of schedule.

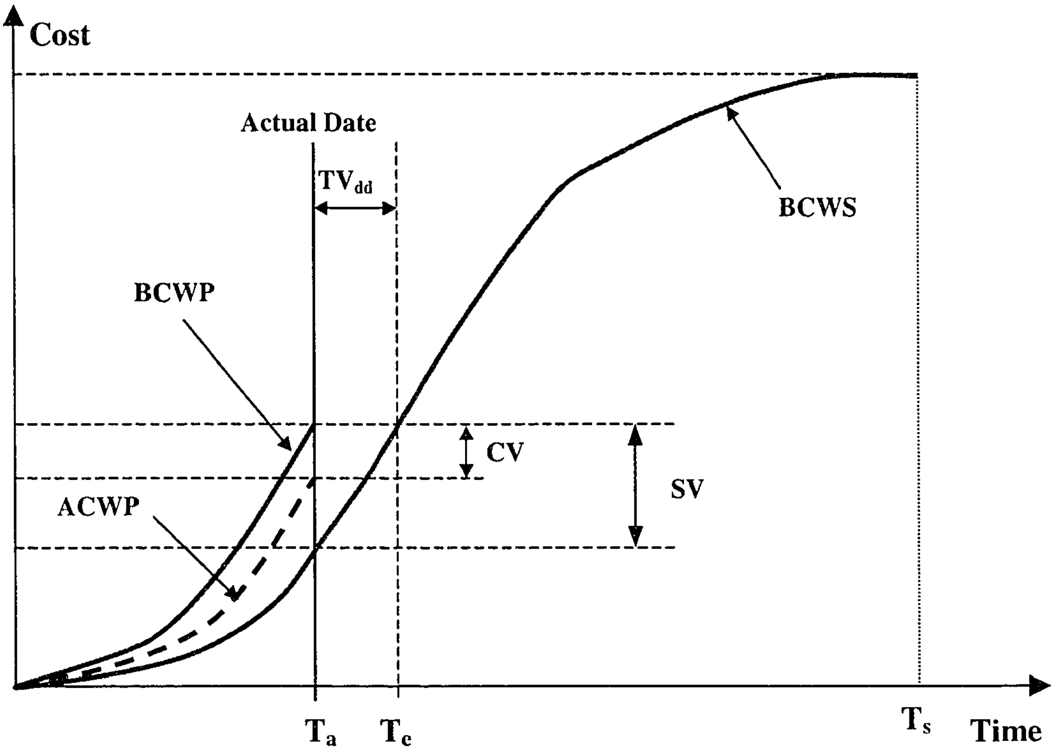


Figure 3. 9 Earned Value S-curves showing Cost, Schedule, and Time Variances

Time Variance At-Completion

The above analysis is based on a project duration consisting of twenty reporting periods (t=20) and assuming that the project will be completed as scheduled, i.e. the expected Schedule Performance Index (SPI) at t = 20 equals 1.0. In other words, at time t=20, the forecasted project completion time (T_f) is equal to the scheduled project completion time (T_s) and the forecasted time variance is zero. In many cases, the project completion could be delayed beyond the scheduled completion date in which case the time variance at completion (TV_{ac}) is negative and SPI < 1.0. Using the *Markov Expected First Passage Time* as explained earlier, we could estimate the time or number of periods before SPI goes back to 1.0 for the first time (after *t=20*) and all the project work is completed. In this case, the *first passage time (T_{SC})* of changing from performance condition *"S =F or D"* (*poor* or *below target*) to *"C"* (on *target*) is the number of periods made by a Markov process as it goes from state *"F or D"* to state *"C"* for the first time.

It should be noted that if SPI is < 1 at the scheduled project completion time (T_s), then it will never be 1.0 again except when all the budgeted work is earned and the project is completed. This is very obvious because the budgeted cost of work scheduled (BCWS) is equal to the budgeted cost of work performed (BCWP) at (T_s). In this case, SPI (BCWP/BCWS) at (T_s) will tend to increase gradually until it is one at (T_f) at which point the project the completed.

If the forecasted time variance at completion (TV_{ac}) is expressed in number of reporting periods and is defined as the expected first passage time (T_{SC}), then the forecasted project completion time (T_f) is equal to the scheduled project completion time (T_s) plus the forecasted time variance at completion (TV_{ac}). (TV_{ac}) and (T_f) can be expressed mathematically as follows:

$$TV_{ac} = -T_{SC} = T_s - T_f \qquad \text{Equation (3.76)}$$

$$T_f = T_s + T_{SC} \qquad \text{Equation (3.77)}$$

The concept of the forecasted time variance at completion (TV_{ac}) is illustrated graphically in Figure 3.11. The figure shows that the time variance to-date is negative since T_e is < T_a. Also, the time variance at completion (TV_{ac}) is negative since T_s is < T_f.

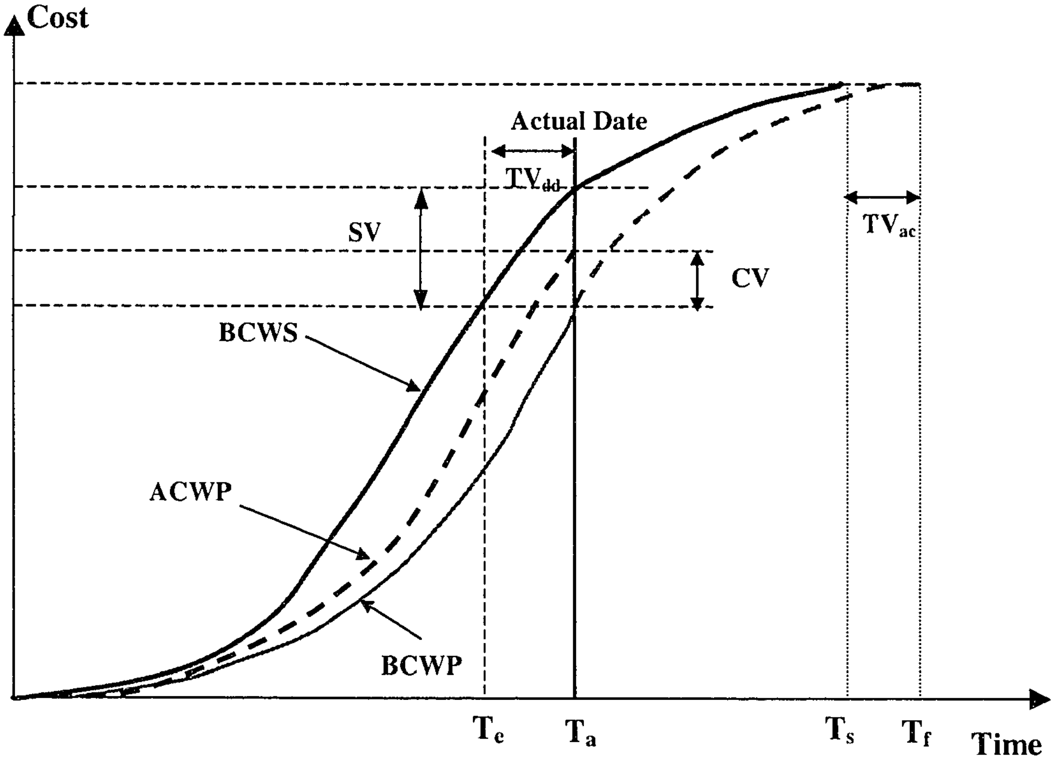


Figure 3. 10 Earned Value S-curves showing the Time Variance At-Completion

3.5 Advantages of the proposed Project Performance Forecasting Model (PPFM)

Modeling the project performance system as a Markov process can provide an adequate forecasting tool for decision makers or project leaders. The presented Markovian forecasting model can predict the performance of each index as well as the overall performance. It uses the initial state probabilities and the estimated transition probabilities plus some other user input parameters and works with the optimization module developed in chapter 4 to search for effective corrective action plans. The advantages of this system can be summarized as follows:

- **Dynamic and Timely Forecasting**

During the first half of the project, as measured by the budget percent complete, it is particularly important to get warnings about significant overruns so that decision makers can react and implement corrective action plans. The proposed system can study the dynamic and stochastic behaviour of performance and provides forecast the condition for any index or for the total project at completion or at any other interim period. Moreover, this tool can provide answers to many queries that are very helpful to the user such as:

  - How many periods (e.g. weeks) will it likely take the project to move from one condition to another, say from ***poor*** performance to ***within target***?
  - What is the probability of the system performance being ***above target*** (state B) after "***n***" reporting periods?
  - In the long run, which status is occupied by the system most frequently and the % of time the system is occupied by each of the possible states?

- **Ability to conduct what-if Scenarios**

The model can be used to optimize the project performance, using the optimization model presented in Chapter 4, by generating what-if scenarios based on many corrective action plans thus assisting decision makers to select and implement highly successful plans.

- **Ability to incorporate historic and current trends**

The model can incorporate the latest changes in the project environment, through expert input, to evaluate future project performance. The model is also designed to incorporate historic and current performance data for better forecasting.

- **Ability to model project uncertainties and subjective conditions**

The presented Markovian forecasting model has the ability to capture the non-quantifiable project conditions like weather and relationship with client and the uncertainty of many factors such as: uncertainty in the initial conditions and uncertainty in the transition probability matrices.

3.6 Conclusion

One of the challenges facing the construction industry is timely and accurate prediction of the stochastic project performance process. The stochastic Markov-chain model is used to model project performance because of its ability to capture the time-dependence and uncertainty of the forecasting process. The Markov chain approach improves on existing, accepted performance forecasting methods. A dynamic Markov model was required to model the performance forecasting model. The proposed model offers a new, quantitative approach to analyze and forecast project performance over time. When integrated with the optimization module presented in Chapter 5, the model can be used to forecast and optimize performance under various corrective action scenarios.

The major contribution of this study is the application of a dynamic multi-state Markov model to forecast the performance of construction projects. While the presented methodology is developed to handle lump sum construction projects, it is generic enough that it may be modified to address additional types of contracts and project phases.

This study proposed an innovative forecasting method using *Dynamic Markov Chains* to predict project performance at completion and at any interim point. The proposed mathematical processes and equations are not for managers and users to learn and understand, but to use them in the form of a smart tool. However, the decision maker should be able to: (1) provide the required input, (2) incorporate his judgment, and (3) analyze and utilize the system to make more informed decisions. The following conclusions are made:

- The study evaluated various subjective, simulation-based, deterministic and stochastic mathematical methods and concluded that there is no single forecasting method that is accurate and applicable for all projects and under all circumstances. Under certain conditions, some simple techniques using trend analysis might produce better forecasts than sophisticated mathematical methods.

- The proposed method, although systematic and is based on mathematical background, has the capability to incorporate judgmental feedback from experts to tune the final forecasted figures. At the same time, although the project manager's talent or intuition has been a significant factor for the project's success, a firm forecasting strategy must be formulated to compliment the project manager's expertise.

- There is a trade-off between the accuracy of predicting future performance and the potential value of such a prediction. The more you wait after the work commences to carry out a forecast, the more accurate is your prediction of at-completion performance. But it would be of enormous benefit to project managers to be able to make predictions during the early stages of construction so that they take the actual project conditions into account and, yet, still have enough time to manage and increase the performance of the remaining work.

The Markov-based forecasting method is undoubtedly not a simple model and requires a lot of to-date actual and planned data as well as changes in scope to improve the accuracy and timeliness of performance prediction. It should be noted that the proposed model requires accurate and timely user input data to reflect the latest project conditions and other qualitative factors. As with any forecasting model, the results are only as good as the data used to generate them. In this case, some of the required input parameters are not easy to find or require subjective assessment from experienced project practitioners. In-complete or in-accurate input leads to inaccurate performance trends, which in turn will generate misleading forecasts. Each user company, prior to implementation and commitment of resources, must carefully evaluate the benefits of the proposed method against the added costs. It would be of value if future research could compare this approach to other forecasting methods such as those described in the literature review. The model should be calibrated with actual observed performance data to check its consistency with a set of observations before its recommendations are used for decision-making.

Improving our ability to forecast project performance will not, alone, improve productivity. The above-proposed technique will only assist project managers in identifying variances and potential performance problems in a more comprehensive and dynamic way. With timely identification of problematic areas, decision makers can propose more alternatives to reduce negative slippages. The more corrective action alternatives project managers have, the better they are able to act (rather than react) in an efficient way to increase performance.

REFERENCES

AACE (1992). *Skills and Knowledge of Cost Engineering,* American Association of Cost Engineers, Morgantown, West Virginia.

Abaza, khaled A., Ashur, Suleiman A., and Al-Khatib, Issam A., (2004). "Integrated Pavement Management System with a Markovian Prediction Model." *Journal of Transportation Engineering*, ASCE, 130(1), 24-33.

Al-Tabtabai, Hashem M., (1998). "A Framework for Developing an Expert Analysis and Forecasting System for Construction Projects." *Expert Systems With Applications*, 14(3), 259-273.

Al-Tabtabai, H.M., (1996). "Modeling Knowledge and Experience to Predict Project Performance." *Project Management Institute 27th Annual Seminar/Symposium*, Boston, Massachussetts, 95-98.

Alshaibani, A., (1999). *A Computerized Cost and Schedule Control System for Construction Projects*, Masters Thesis, Civil, Building and Environmental Engineering, Concordia University, Montreal, Canada.

Barraza, Gabriel A., Back, W. Edward, and Mata, Fernando, (2004). "Probabilistic Forecasting of Project Performance Using Stochastic S Curves." *Journal of Construction Engineering and Management*, ASCE, 130(1), 25-32.

Boussabaine, A.H., and Elhag, T., (1999). "Applying Fuzzy Techniques to Cash Flow Analysis." *Construction Management and Economics*, 17(6), 745-755.

Brown, Joseph M., (1996). "Going for the Goal, Forecasting." *AACE Transactions, C&S/M&C.1*, AACE International, Morgantown, WV.

Bunn, Derek W., (1982). *Analysis for Optimal Decisions*, John Wiley & Sons Ltd, New York.

Christensen, David S., (1993). "Determining an Accurate Estimate at Completion." *National Contract Management Journal*, 25: 17-25.

Christensen, David S., Antolini, Richard C., and McKinney, John W., (1995). "A Review of Estimate at Completion Research." *Journal of Cost Analysis and Management*, Spring Issue, 41-62.

Choi, Jongsoo, Russell, Jeffrey S., and Miller, Robert B., (2003). "Forecasting Performance Evaluation: Does a Complicated Model Outweigh a Simple One?" *Proceedings of the Construction Research Congress*, ASCE, 95-102.

Collopy, F. and Armstrong J. S., (1992). "Rule-based forecasting: Development and validation of an expert systems approach to combining time series extrapolations." *Management Science,* 38(10), 1394-1414.

Dawood, Nashwan, and Molson, Angelo, (1997). "An Integrated Approach to Cost Forecasting and Construction Planning for the Construction Industry." *Proceedings of the Fourth Congress on Computing in Civil Engineering*, Philadelphia, Pennsylvania, June 16-18, pp. 535-542.

Diekmann, J.E., and Al-Tabtabai, H., (1992). "Knowledge-Based Approach to Construction Project Control." *International Journal of Project Management*, 10(1), 23-30.

Eldin, Neil N., and Hughes, Robert K., (1992). "An Algorithm for Tarcking Labor Cost." *Cost Enginnering*, 34(4), 17-23.

Farghal, Sherif H., and Everett, John G., (1997). "Learning Curves: Accuracy in Predicting Future Performance." *Journal of Construction Engineering and Management*, ASCE, 123(1), 41-45.

Fayek, A.R., (2000). "Developing a Fuzzy Reasoning Approach for Construction Project Control." *Proceedings of 2000 NSF Design and Manufacturing Research Conference*, Vancouver, British Columbia.

Fleming, Quentin W., and Koppelman, Joel M., (2002). "Using Earned Value Management." *Cost Engineering*, 44(9), 32-36.

Fleming, Q. W., and Koppelman, J. M., (1995). "The Earned Value Body of Knowledge", *PM Network*, Project Management Institute, May.

Fleming, Q. W., and Koppelman, J. M., (1994). "The Essence of Evolution of Earned Value." *Cost Engineering*, AACE, 36(11), 21-27.

Georgy, Maged E., Chang, Luh-Maan, and Zhang, Lei, (2005). "Prediction of Engineering Performance: A Neurofuzzy Approach." *Journal of Construction Engineering and Management*, ASCE, 131(5), 548-557.

Gillespie, Daniel T., (1992). *Markov processes: an introduction for physical scientists*, Academic Press Inc., San Diego, CA 92101.

Guignier, Frederic, and Madanat, Samer, (1999). "Optimization of Infrastructure Systems Maintenance and Improvements Policies." *Journal of Infrastructure Systems*, ASCE, 5(4), 124-134.

Hill, Lawrence S., (1970). “The Delphi Process: A Tool for Business Forecasting.” *AACE Transactions*, AACE International, Morgantown, WV, pp. 101-104.

Isidore, Leroy J., and Back, W. Edward, (2002). “Multiple Simulation Analysis for Probabilistic Cost and Schedule Integration.” *Journal of Construction Engineering and Management*, ASCE, 128(3), 211-219.

Khosrowshahi, Farzad, (1988). “Construction Project Budgeting and Forecasting.” *AACE Transactions, C.3*, AACE International, Morgantown, WV.

Knight, K. and Fayek, A. R., (2002). “Use of Fuzzy Logic for Predicting Design Cost Overruns on Building Projects.” *Journal of Construction Engineering and Management*, ASCE, 128(6), 503-512.

Koksal, Almula, and Arditi, David, (2004). “Predicting Construction Company Decline.” *Journal of Construction Engineering and Management*, ASCE, 130(6), 799-807.

Lee, Dong-Eun, (2005). “Probability of Project Completion Using Stochastic Project Scheduling Simulation.” *Journal of Construction Engineering and Management*, ASCE, 131(3), 310-318.

Li, Ji, (2004). *Web-based Integrated Project Control*, Doctoral Dissertation, Concordia University, Montreal, Canada.

Mazzini, Richard A., (1991). “Momentum Theory: A New Technique for Cost Analysis.” *AACE Transactions, I.4*, AACE International, Morgantown, WV.

Micevski, Tom, Kuczera, George, and Coombes, Peter, (2002). “Markov Model for Storm Water Pipe Deterioration.” *Journal of Infrastructure Systems*, ASCE, 8(2), 49-56.

Morcous, G., Lounis, Z., and Mirza, M.S., (2003). “Identification of Environmental Categories for Markovian Deterioration Models of Bridge Decks.” *Journal of Bridge Engineering*, ASCE, 8(6), 353-361.

Nay, L.B. and Logcher R.D., (1986). "Proposed Operation of an Expert Systems for Analyzing Construction Project Risks", *Proceedings of the Ninth Conference on Electronic Computation*, ASCE, edited by Kenneth M. Will, February 23-26, pp.65-76.

Neil, J., (1987). *Project Control for Construction*, Construction Industry Institute, Publication 6-5, University of Texas, Austin, Texas.

Patten, William Neff, (1987). “Construction Production Forecasting: A Modeling Approach.” *Cost Engineering*, AACE, 29(4), 11-15.

Robinson, R. L., and Abuyuan, A. O., (1996). "Simplified Performance Estimators (SPEs.)" *Project Management Institute 27th annual Symposium*, Boston, MA., USA, 191-197.

Seiler, James, (1983). "Cost and Schedule Data Analysis and Forecasting." *Project Management Institute Symposium*, Houston, USA, 17-19 October, 1983.

Shtub, A., Bard, J. F., and Golberson, S., (1994). *Project Management-Engineering, Technology and Implementation*, Prentice Hall, Inc., Englewood Cliffs, N.J.

Singh, Amarjit, (1993). "Non-Linear Earned Value Analysis." *AACE Transactions, C.16*, AACE International, Morgantown, WV.

Teicholz, Paul, (1993). "Forecasting Final Cost and Budget of Construction Projects." *Journal of Computing in Civil Engineering*, ASCE, 7(4), 511-529.

Touran, Ali, (1997). "Probabilistic Model for Tunneling Project Using Markov Chain." *Journal of Construction Engineering and Management*, ASCE, 123(4), 444-449.

Ward, S. A., and Lithfield, T., (1980). *Cost control in design and construction*, McGraw-Hill, New York.

Wheelwright, C., (1995). *Forecasting methods for management*, 4th ed., Wiley, New York.

Willis, R. E., (1987). *A Guide to Forecasting for Planners and Managers*, Prentice Hall, Englewood Cliffs, NJ.

Zayed, Tarek M., Chang, Luh-Maan, and Fricker, Jon D., (2002a). "Statewide Performance Function for Steel Bridge Protection Systems." *Journal of Performance of Constructed Facilities*, ASCE, 16(2), 46-54.

Zayed, Tarek M., Chang, Luh-Maan, and Fricker, Jon D., (2002b). "Life-Cycle Cost Analysis using Deterministic and Stochastic Methods: Conflicting Results." *Journal of Performance of Constructed Facilities*, ASCE, 16(2), 63-74.

Zwikael, O., Globerson, S. and Raz, T., (2000). "Evaluation of Models for Forecasting the Final Cost of a Project." *Project Management Journal*, 31(1), 53-57.

Chapter 4

Corrective Action Optimization in Construction Projects using Genetic Algorithms

4.1 Introduction

The success of projects depends on sound construction management (Bush 1973). Construction management is a process of achieving project objectives by using resources. A project objective breakdown structure as presented in Chapter 2 is used to define and optimize the overall performance of a construction project. Project performance optimization using deterministic mathematical models is very critical and challenging because the corrective action process within construction projects is complex and ill structured.

Progress measurement and forecasting are necessary to monitor the deviation of actual vs. planned progress but are not sufficient. Total project control requires the selection and implementation of effective corrective action measures. When a project slips behind the baseline, corrective action plans should be selected and carried out to get the project back into target. Since there are numerous corrective action activities available to a construction project, it is almost impossible to evaluate all the possible combinations and propose an adequate corrective action plan in a timely and cost efficient manner. We cannot increase one performance aspect independently of other aspects. For example, in a project with poor schedule performance, the project manager would typically react to the slippage by attempting to close the gap as fast as possible. This type of response may produce more problems than it solves, and it may amplify slippages in the overall project performance. Any corrective action plan will impact one or more aspect of performance and the enhancement of this performance could be achieved by applying an adequate optimization technique, which is the subject of this chapter. It should be emphasized that the output of the model is a *computed optimal plan* based on the information provided by users and is not necessarily the *best plan* of action in the absolute sense.

The development of such an optimal plan is an extremely challenging task, even for a small number of activities. The challenge arises because of the combinatorial nature of the problem, the various constraints, and the non-linearity of the objective function. Proper selection and implementation of corrective action plans have long been recognized as significant to the success of any project but there has been no comprehensive solutions proposed. Most of the current project management tools have mainly focused on performance measurement and forecasting but did not attempt to select corrective action plans in response to negative performance variances throughout the construction phase. It should be noted that some research proposed mechanisms for selecting corrective actions using experts systems without addressing the optimization problem (Diekmann and Al-Tabtabai 1992). Due to these issues, the development of an optimization tool is a very helpful tool for efficient and effective selection of corrective action plans. The classical mathematical tools cannot solve these complex problems without oversimplification. Being considered as a powerful optimization technique for locating the global optimal, genetic algorithms (GAs) are proposed to assist decision-makers to identify better corrective action plans.

The proposed model is based on the performance measurement (IPPM) and forecasting (PPFM) models presented in Chapters 2 and 3 respectively and utilizes GAs to determine the *calculated optimal* corrective action plan that maximizes the overall performance at the end of the project. The selected plan defines a set of corrective action activities and the associated timing of execution.

The following sections briefly introduce the traditional mathematical methods. Genetic algorithms, its applications, and advantages are then presented. Next, the optimization problem is discussed and its mathematical foundation described. A GA based algorithm for solving the problem is then outlined. Tuning the proposed model and conclusions are made in the last sections.

4.2 Mathematical Methods

Conventional search methods can be classified into three main types: calculus-based, enumerative, and random. Although calculus-based optimization methods have been improved, they still lack robustness (Goldberg 1989). Their dependence upon continuity and derivative existence are not suitable for the domain problem at hand. The enumerative search techniques, e.g. dynamic programming, determines the objective function values at every point in the space, one at a time. This is a simple and attractive optimization tool for problems where the number of possibilities is small, but it lacks efficiency in many practical problems where the search space is very large like the problem of performance optimization. Random search algorithms that search and save the best solution must also be discounted because of the efficiency problem. Random searches in the long run are not better than enumerative techniques and lack robustness (Goldberg 1989).

Although the traditional optimization methods are not robust, they can be very useful if integrated with genetic algorithms. These hybrid systems have been used successfully in many applications like in Kim et al. (2004), Marzouk and Moselhi (2004), and Leu et al. (2001).

4.3 Genetic Algorithms

4.3.1 Introduction

Genetic Algorithms (GAs) are search algorithms based on the mechanics of natural selection and natural genetics. GAs was developed by John Holland, his colleagues, and students at the University of Michigan (Goldberg 1989). Based on simplifications of natural evolutionary processes, genetic algorithms operate on a population of solutions rather than a single solution and implements heuristics such as selection, crossover, and mutation to evolve better solutions. GAs employ a random yet directed search using the process of natural evolution and "survival of the fittest" principle for locating the global optimal solution.

In real life, the DNA structure encodes the characteristics of the organism; likewise, a *genotype* stores the characteristics of artificial organisms in GAs. The *genotype* is a long string of bits that represents a set of decisions, a potential solution to a problem. Every solution to the problem should be represented in a string format. Such a presentation is referred to as a *chromosome*. Conventionally, binary strings represent solutions.

The optimization process using GAs starts by encoding and mapping solutions into chromosomes. The generation of an initial population of random solutions can then follow. The members of the population are evaluated based on their fitness, modified using genetic operators, and replaced in cycles called generations. Strings with better fitness value are more likely to survive than the ones with lower values. The evolution process continues over many generations until the strings in the new generation are identical or a specified termination criterion is met. Within the GA environment, hundreds of possible solutions can compete with one another but only the "fittest" survives.

4.3.2 Solution Representation (Encoding) in GAs

Every solution to the problem should be represented in a string format. Such a presentation is referred to as a *chromosome*. Conventionally, binary strings represent solutions, but the use of floating-point representation has gained increasing acceptance among GA practitioners and is as effective as binary coding, and in some applications makes the coding more natural (Chan et al. 1996). Three issues impact the selection of a suitable chromosome representation: the decision variable being coded, the mapping from activity to gene position, and the form of coding to be used for gene values (Chan et al. 1996).

4.3.3 Genetic Operators

There are three basic operators in the basic GA system: selection, crossover, or mutation. The selection process is to enable the strings with a good fitness values to survive into the next generation. Crossover is a process where the "good" solutions are coupled to generate “better” ones (Goldberg 1989). Mutation is the random alteration of one of the genes in the chromosome to provide diversity in a population. A brief description of the genetic operators is presented below:

Selection

According to the survival-of-the-fittest mechanism, fitter solutions survive, while weaker ones die. Through selection, a fitter chromosome survives to the next generation and produces off springs according to its level of fitness. There are different types of selection and proportionate selection is probably the most common procedure that uses the Roulette wheel technique as described by Goldberg (1989).

Crossover

Crossover is a structured yet random information exchange between two strings. It is performed by randomly selecting two solutions from the population and exchanging their genes information. The chromosomes that are not selected for crossover remain unchanged and copied into the next generation. The objective of this operator is to generate *better* solutions from *good* ones.

Mutation

The mutation operation is implemented to restore some genetic information that may have been lost after the application of crossover for some generations. In this way, GAs can visit regions of the search space, which are not normally explored using other optimization techniques. It can prevent a too-rapid takeover by some dominating chromosomes that may only represent local optimal solutions.

Although it is obvious that GAs are probabilistic in nature, they are not mere random “search” engines but are guided throughout the optimization process. For a detailed description of GA principles and the schema theorem, the reader is referred to Goldberg (1989).

4.3.4 Genetic Algorithms – An adequate tool

It should be noted that the functioning of genetic algorithms does not always guarantee success. It is governed by stochastic rules and a too fast convergence may halt the process of evolution. Nevertheless, these algorithms are extremely efficient and are used in fields ranging from stock exchange to scheduling of assembly robots. Since they operate on more than one solution at a time, genetic algorithms are typically effective at both the exploration and exploitation of the search space. As a result, GAs are considered an adequate tool for determining optimal solutions of complex and large-scale problems. Direct representation of problems, i.e. use of data types to represent chromosomes instead of bit strings, renders genetic algorithms more applicable and robust. Continued decrease in computational cost and increase in speed make genetic algorithms viable tools despite their huge computational requirements. The reader is referred to Goldberg (1989) who provided a comprehensive description of genetic algorithms.

4.4 GA applications

Since Genetic Algorithms (GAs) are generic and need little knowledge and information about the problem domain, they are applied to solve many science and engineering optimization problems (Goldberg 1989). GA literature includes numerous applications in civil engineering and construction management. Some research has been done in the optimization of construction facilities layouts using GAs. There are also many other applications of GAs in planning and scheduling but none in the area of corrective action optimization based on total project performance. The following is a summary of some GAs applications in the domain of Construction Management.

4.4.1 Scheduling and Cost Optimization of Construction Projects

GAs have been used by the following researchers:

- Feng et al. (2004) used GAs to optimize the schedule of dispatching Ready Mix Concrete trucks.

- Hegazy et al. (2004) presented a model for schedule and cost optimization of infrastructure projects that involve multiple distributed sites.
- Marzouk and Moselhi (2004) combined computer simulation with genetic algorithms to optimize earthmoving operations.
- Senouci and Eldin (2004) presented an augmented Lagrangian genetic algorithm model for resource scheduling.
- Zheng et al. (2004) applied a GA-based multi-objective approach for time-cost optimization.
- Hegazy and Kassab (2003) presented a new approach for resource optimization using combined simulation and genetic algorithms.
- Zheng et al. (2003) used GA-based technique to optimize multi-resource leveling.
- Que (2002) implemented GAs for time-cost optimization.
- Hegazy and Wassef (2001) developed a practical model for schedule and cost optimization of repetitive projects.
- Leu et al. (2001) introduced a GA-based fuzzy optimal model for construction time-cost trade-off.
- Leu and Yang (1999) optimized the schedule duration considering multi-criteria.
- Al-Tabtabai and Alex (1997) used GAs to optimize manpower scheduling.
- Feng et al. (1997) and Li and Love (1997) presented an algorithm for construction time-cost trade-off optimization using GA principles.
- Chan et al. (1996) proposed a new approach for resource scheduling using GAs.

4.4.2 Optimization of Construction Site Layout

Optimization of the layout of temporary facilities using genetic algorithms attracted the attention of many researchers. Mawdesley et al. (2002) formulated the site layout problem as a sequence-based genetic algorithm. Chau (2004) and Li and Love (1998) presented a model for allocation of construction facilities with genetic algorithms.

4.4.3 Construction Cost Estimating and Control

Kim et al. (2004) proposed a neural network model incorporating a genetic algorithm for estimating construction costs. Hegazy and Petzold (2003) used Genetic optimization for dynamic project control.

The successful implementation of genetic algorithms in the above research is due to many advantages that are summarized in the next section.

4.5 Genetic Algorithms vs. Traditional Methods

Most of the Conventional optimization techniques, utilizing the hill climbing routine and the gradient based method, do not guarantee the location of the global optimal solution if the solution space is non-convex which is the case with the optimization problem at hand. In addition, these methods are not adequate to handle problems where the solution space is discontinuous.

In the language of genetic algorithms, the search for an optimal solution to a problem is a search for the best string or chromosome. This is the fittest chromosome based on the model assumptions and users input, which is not necessarily the best solution for the problem at hand. The space of all possible chromosomes can be viewed as an imaginary landscape where valleys correspond to strings that represent poor solutions, and the landscape's highest summit corresponds to the best possible string or solution. Hill climbing is one conventional technique for exploring such a landscape. It starts at some random point, and if the quality of the solution improves it continues in that direction, otherwise it selects the other direction. The problem at hand is a complex one with a landscape containing many topological features. Finding the right solution or even the right direction within the enormous search space becomes increasingly difficult.

Genetic algorithms, proposed by Holland J. (1975), can overcome the above-mentioned drawback by casting a net over this landscape and searching many regions simultaneously. The ability of genetic algorithms to focus on the most promising parts of a solution space is due to their ability to combine strings containing partial solutions. GAs are thus considered adequate tools for dealing with problems having enormous search spaces like project performance optimization. Some of the advantages of genetic algorithms over the conventional methods are as follows:

- GAs do not experience combinatorial explosion. Genetic algorithms can explore a far wider range of potential solutions to a problem than do conventional tools.
- GAs do not need thorough understanding of the problem space. Whereas traditional methods implement rules specific to the model or constraint formulation.
- GAs do not need gradient information. They can be applied to non-differentiable functions and consequently can handle a wide variety of problems and objective functions (Goldberg 1989).
- GAs work with a population of points instead of a single point (Goldberg 1989).
- GAs provide a set of optimal and near optimal solutions and not only one optimal solution, as is the case with the many traditional optimization tools.
- The GAs operators use stochastic decision rules instead of deterministic rules (Goldberg 1989). This randomness makes the search unbiased toward any particular zone in the search space. It also increases the chance of recovery from a mistake.
- GAs work with a coding of the parameter set, not the parameters themselves (Goldberg 1989).

Due to the above advantages, GAs have received significant attention regarding their potential as a robust optimization technique (Gen and Cheng 1997). Also, the above characteristics render GAs an efficient and effective tool to handle construction optimization cases where the exploration space is extensive.

4.6 Multi-objective Optimization

Many practical optimization problems involve several criteria that need to be evaluated simultaneously, and it is not possible or wise to integrate these into a single criterion. In this case, the problem is said to be a *multi-objective* or *multi-criteria* optimization problem. The idea of genetic search in multi-objective problems dates back to the early dates of GA experimentation (Goldberg 1989). Recently, genetic algorithms have been applied in time-cost multi-objective optimization (Zheng et al. 2004 and Leu and Yang 1999).

In multi-objective optimization, there is no precise definition for the "optimum solution" as in the case of a single objective. In other words, none of the feasible solutions will satisfy the simultaneous optimum for all objectives. As a result, optimality has a different meaning because it has to respect the integrity of each of the separate objectives or criteria. The concept of *Pareto optimality* is a proven and widely applied method to handle this type of optimization by identifying non-dominated solutions (Marzouk and Moselhi 2004). Using this concept, instead of obtaining a single optimal solution, we obtain a set of solutions that are not dominated by any others (Goldberg 1989). This set is called the Pareto optimal set. It is obvious that the concept of Pareto optimality does not assist the decision maker to select a single solution from the Pareto optimal set. The decision maker must use his experience and judgment to arrive at a particular course of action.

4.7 Project Performance: A Single Objective Optimization Problem

Like many real-world decision-making problems, the project performance optimization problem involves many conflicting objectives. For example, it may be possible to increase the schedule performance objective by assigning more expensive resources to work, but then the cost performance index (CPI) of the project will decrease. In this regard, performance optimization can be classified to a great extent as a multi-objective optimization problem. In this study, the multi-objective optimization problem is transformed into a single-criterion problem. A model integrating the eight performance indices into one overall performance objective was proposed in Chapter 2. The model uses the analytical hierarchy process (AHP) to assign weights for each objective and aggregate the weights into one overall objective value that can be optimized. The reader is referred to Chapter 2 for further details about this methodology.

The optimization problem is thus reduced to a single criterion and consequently there is no need to search over multiple objectives. In single-criterion optimization, we simply seek the best feasible value of the well-defined objective function, or the highest project performance index in our case. The objective function will then be transformed into a fitness function form as will be explained in Section 4.10.4.

4.8 Development of Project Performance Objective Function

In its most general form, the performance optimization problem asks the following: Given a set of corrective action activities, their impact on the performance objectives, set of constraints, and a measurement of the overall performance, what is the best plan or combination of activities such that the overall performance at the end of project is maximized. It should be noted that the most significant goal of optimization is improvement. It would be nice to select the best solution, but perfection in the world of construction is almost impossible and this model may not attain optimality but will definitely improve the decision-making process. An optimal solution in this context is not necessarily the *perfect solution*; it is only the *best-computed solution.*

Almost every corrective action plan have negative and positive impacts on the multiple conflicting performance objectives thus leading to increased problem complexity. In this section, a systematic approach to develop a project performance objective function is presented in five parts.

4.8.1 Input Parameters

There are two areas that require the users' input. The first area is the *corrective action decision matrix*, which lists all feasible and viable corrective action activities available to the construction management team at that point of the project.

Table 4.1 displays a matrix of possible corrective action activities that are initiated by the various agents or departments to enhance performance in their respective areas and to possibly achieve the target objectives. If the number of proposed activities to enhance each of the eight performance indices are: c, s, p, b, f, q, t, and l respectively, then the total number of activities in the matrix is "n" and is calculated using equation (4.1).

$$n = c + s + p + b + f + q + t + l \qquad \text{Equation (4.1)}$$

Table 4. 1 Corrective Action Decision Matrix

Agent/Area	**Suggested Corrective Action Activities**					
1. Cost	C-01	C-02	...	...	...	C-c
2. Schedule	S-01	S-02	...	...	...	S-s
3. Billing	B-01	B-02	...	...	...	B-b
4. Profitability	P-01	P-02	...	...	...	P-p
5. Safety	F-01	F-02	...	...	...	F-f
6. Quality	Q-01	Q-02	...	...	...	Q-q
7. Team Satisfaction	T-01	T-02	...	...	...	T-t
8. Client Satisfaction	L-01	L-02	...	...	...	L-l

The second input parameter is the *impact matrix*, which includes the impact and timing data of each activity on the eight performance indices of the project. Table 4.2 shows the impact level of activity "S-01" on the various performance areas. It should be noted that every activity could be initiated within an activation range as defined by the decision maker. Also, that same activity, although proposed by a single agent or department, can have either positive or negative impact on the performance of other project indices at different periods. In the Activity Impact Matrix shown in Table 4.2, activity S-01: Utilize Robot for Painting ", proposed by the schedule agent to minimize slippage, has medium positive impact (+M) on schedule within the time framework [T_{DD+10},T_{DD+12}], low negative impact (-L) on cost within the time framework [T_{DD+1},T_{DD+3}] and low positive impact (+L) on Safety within the time framework [T_{DD+10},T_{DD+12}]. There is no impact on the other performance indices. Note that T_{DD} is the data date or time at which the corrective action is proposed and that activity "S-01" can be implemented at T_{DD+10}, or T_{DD+11} or T_{DD+12}.

Table 4. 2 Corrective Action Impact Matrix for activity "Utilize Robot for Painting"

Agent/Area	T_{DD}	T_{DD+1}	T_{DD+2}	T_{DD+3}	…	T_{DD+10}	T_{DD+11}	T_{DD+12}
1. Cost		-L	-L	-L				
2. Schedule						+M	+M	+M
3. Billing								
4. Profitability								
5. Safety						+L	+L	+L
6. Quality								
7. Team Satisfaction								
8. Client Satisfaction								

A corrective action plan can be composed of one or many corrective action activities implemented at their respective activation time. This means that the number of possible plans can be very large as will be demonstrated under section 4.9.1 "Combinatorial Explosion". Each corrective action activity will positively or negatively impact the probability transition curves. A mechanism to consolidate and quantify the impact is proposed in the next section.

4.8.2 Quantification of Impact on Transition Probability Curves

The impact of all the activities within each corrective action plan on every performance index needs to be consolidated and quantified. The net impact value, expressed as a %, will be used to modify the transition probability curves (TPC's) as will be explained in sections 4.8.3 and 4.8.4.

The decision maker will input the timing and level of impact for each activity as shown in Table 4.2. To convert the qualitative assessment of the decision maker into a numerical figure, table 4.3 is proposed and could be modified to meet specific project conditions.

Table 4. 3 Level of Impact Conversion Table

Level of Impact (I_L)	**Increase / Decrease in Transition Probability Curve**
Very High (VH)	+/- 10 %
High (H)	+/- 8 %
Medium (M)	+/- 4 %
Low (L)	+/- 2 %
Very Low (VL)	+/- 1 %
Nil (N)	0

Based on the input provided by experts in the form of impact matrices as shown in section 4.8.1, the algorithm, using the conversion scale proposed in Table 4.3, filters and consolidates the impact of all activities. For example, the qualitative levels of impact that experts provide for corrective action activities (A, B, &C) in a specific plan (P_l) are converted into one value at a specific time expressed in terms of "L". In this case, "L" indicates "Low" level of impact. To illustrate this notion, Table 4.4 shows the cumulative impact of all activities on the CPI as +2L and +6L at T_{DD+1} and T_{DD+3} respectively or 4% and 12% in numerical values as per the conversion scale proposed in Table 4.3.

Table 4. 4 Impact Matrix for Corrective Action Plan (P1) on the Cost Index (CPI)

Corrective Activity	T_{DD}	T_{DD+1}	T_{DD+2}	T_{DD+3}	..	T_{DD+10}	T_{DD+11}	T_{DD+12}
1. A		+M						
2. B				+M				
3. C				+H				
Net Cumulative Impact (*I*)		**+2L**		**+6L**				

4.8.3 Calculating the magnitude of adjustment (M_v)

Each corrective action activity can have positive, negative, or no impact on each of the eight performance indices and consequently the probability transition curves need to be modified. In order to modify the curves using a methodology proposed in the next section, the net cumulative impact (I) at various time periods must be converted into what is called "*Magnitude of Adjustment*", M_v. Due to the law of diminishing return, M_v increases at a decreasing rate as I increases. Equation (4.2) is proposed in this research to relate M_v to the net cumulative impact (I).

$$M_v = 1 - e^{I \ln(1-a_o)} \qquad \text{Equation (4.2)}$$

Where

M_v is the *magnitude of adjustment* to the transition probability curves in %.

I is the *net cumulative impact*, obtained by summing up the level of impact of all activities on a certain performance index at a specific period of time expressed in terms of "L", and

a_o is the numerical value for low impact "L" as a fraction. Although this study proposes a 2% value as shown in Table 4.3, a_o is an input parameter and should be defined by the decision maker to reflect the real project conditions.

Figure 4.1 shows the general curve of M_v as a function of I based on Equation (4.2). It is a generic relationship and can be modified to reflect the judgment of the decision-maker and the latest project conditions. This is achieved by introducing a correction factor ***F*** as shown in Equation (4.3).

$$M_v = F[1 - e^{I \ln(1-a_o)}] \qquad \text{Equation (4.3)}$$

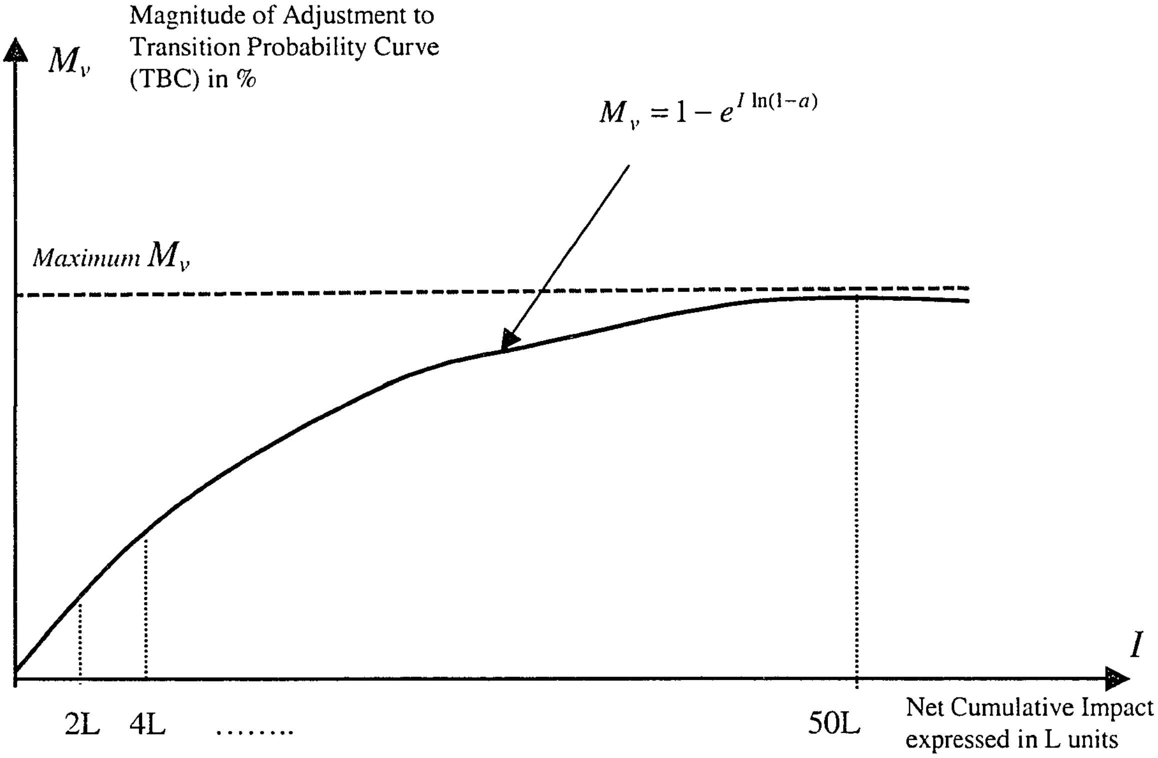


Figure 4. 1 Relation between the Magnitude of Adjustment and the level of impact (I)

To demonstrate the use of Equation (4.2), assume that a = 0.02 (2%) based on Table 4.3, then M_v can be expressed as:

$$M_v = 1 - e^{-0.0202I} \qquad \text{Equation (4.4)}$$

Using Equation (4.4), M_v is plotted against I as shown in Figure 4.2. The value of adjustment to the CPI transition probability matrix, M_v, at T_{DD+1} (for $I=2L$) is 3.96%, and at T_{DD+3} (for $I=6L$) is 7.46% (11.42% less 3.96%). Since the impact of 3.96% will propagate to the end of project, the impact at T_{DD+3} should be reduced by the same amount. Adjustment of the probability curves for the various transition states based on the obtained M_v values is discussed in the next section.

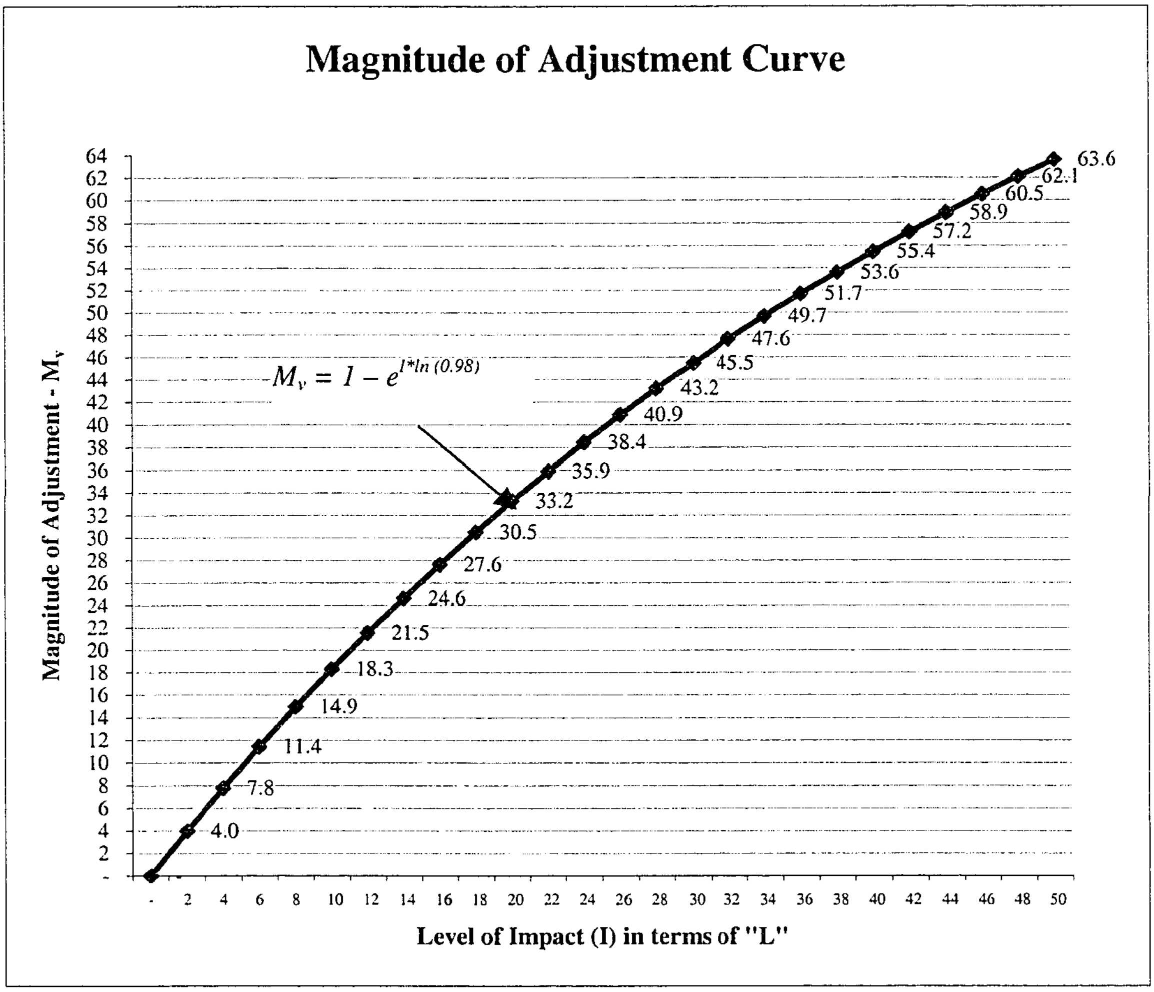


Figure 4. 2 Curve relating the Magnitude of Adjustment (M_v) to level of impact (*I*)

4.8.4 Adjustment of the Transition Probability Matrix

The Original *Transition Probability Function* from state "*i*" to state "*j*" for a certain *performance index (I)* is normally constructed before the start of the project construction phase based on company past records and the planned project S-curves as explained in Chapter (3). As the project progresses, these curves do not necessarily reflect the project specific conditions, the revised S-Curves, or any corrective action plans and consequently need to be revised and adjusted. As a result, the probability matrices need to be updated through out the remaining project duration in order to properly forecast the future performance. The following is a proposed methodology to update the probability matrices for a defined impact percentage value M_v.

Modified Transition Probability Curve

As demonstrated in Chapter (3) for a certain data date t_{dd}, the *revised transition probability* value from performance state "*i*" to state "*j*" for $t > t_{dd}$, defined as $P'_{ij}(t)$ is determined as:

$$P'_{ij}(t) = P'_{ij}(t_{dd}+1) - [P'_{ij}(t_{dd}+1) - P'_{ij}(t_{20})] * [a't^3 + b't^2 + c't + d']$$

$$\text{for } t_{dd}+1 < t < 20 \qquad \text{Equation (4.5)}$$

Where:

$P'_{ij}(t_{dd}+1)$ = *Revised Transition Probability* from performance state "*i*" to state "*j*" at data date time $t_{dd}+1$.

$P'_{ij}(t_{20})$ = *Revised Transition Probability* from performance state "*i*" to state "*j*" at time $t=20$, or at end of project. It is defined by the decision maker or can be calculated using the following Equation:

$$P'_{ij}(t_{20}) = [P'_{ij}(t_{dd}+1) / P_{ij}(t_{dd}+1)] * P_{ij}(t_{20}) \qquad \text{Equation (4.6)}$$

a', b', c', and d' are the new parameters of the forecasted S-curve (updated as at the data date t_{dd}) that is associated with *performance index I* and are automatically calculated by the company project management system.

Once $P'_{ij}(t_{dd}+1)$ is computed, $P'_{ij}(t)$ can be defined for any $t > t_{dd}$ using Equation (4.5) and a *revised transition probability curve* can be generated. The following section outlines a proposed methodology to calculate $P'_{ij}(t_{dd}+1)$.

Modified Transition Probability Matrix at $t_{dd}+1$

Assume that the overall net impact of a certain *corrective action plan C* on *performance index I* has a positive value of M_v at time $t_{dd}+1$. Equation (4.7) shows the transition probability matrix for a specific performance index at time *t*.

$$[\mathrm{P}]^{t} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ F \end{array} \begin{array}{c} \begin{array}{ccccc} A & B & C & D & F \end{array} \\ \begin{bmatrix} P_{AA}(t) & \cdots & \cdots & \cdots & P_{AF}(t) \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P_{FA}(t) & \cdots & \cdots & \cdots & P_{FF}(t) \end{bmatrix} \end{array}$$

Equation (4.7)

Subject to: $\sum_{j=A}^{F} P_{ij}(t) = 1$ for $i = A, B, C, D, \& F$

Using the same notation, the revised matrix at time $t_{dd}+1$, $[\mathrm{P'}]^{t}{}_{dd}^{+1}$, can be defined as shown in Equation (4.8).

$$[\mathrm{P'}]^{t}{}_{dd}^{+1} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ F \end{array} \begin{array}{c} \begin{array}{ccccc} A & B & C & D & F \end{array} \\ \begin{bmatrix} P'_{AA}(t_{dd}+1) & \cdots & \cdots & \cdots & P'_{AF}(t_{dd}+1) \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ P'_{FA}(t_{dd}+1) & \cdots & \cdots & \cdots & P'_{FF}(t_{dd}+1) \end{bmatrix} \end{array}$$

Equation (4.8)

Subject to: $\sum_{j=A}^{F} P'_{ij}(t_{dd}+1) = 1$ for $i = A, B, C, D, \& F$

To quantify the revised matrix $[\mathrm{P'}]^{t}{}_{dd}^{+1}$ due to a positive impact M_v at time $t_{dd}+1$ the following Equations (4.9 – 4.33) are proposed:

Transition Probabilities from State A to other states

$$P'_{AA}(t_{dd}+1) = \max\{100, P_{AA}(t_d) + M_v\}$$ Equation (4.9)

$$P'_{AB}(t_{dd}+1) = 100 - P'_{AA}(t_{dd}+1)$$ Equation (4.10)

$$P'_{AC}(t_{dd}+1) = 0$$ Equation (4.11)

$$P'_{AD}(t_{dd}+1)=0 \qquad \text{Equation (4.12)}$$

$$P'_{AF}(t_{dd}+1)=0 \qquad \text{Equation (4.13)}$$

Transition Probabilities from State B to other states

$$P'_{BA}(t_{dd}+1)=\max\{100, P_{BA}(t_d)+M_v\} \qquad \text{Equation (4.14)}$$

$$P'_{BB}(t_{dd}+1)=100-P'_{BA}(t_{dd}+1) \qquad \text{Equation (4.15)}$$

$$P'_{BC}(t_{dd}+1)=0 \qquad \text{Equation (4.16)}$$

$$P'_{BD}(t_{dd}+1)=0 \qquad \text{Equation (4.17)}$$

$$P'_{BF}(t_{dd}+1)=0 \qquad \text{Equation (4.18)}$$

Transition Probabilities from State C to other states

$$P'_{CA}(t_{dd}+1)=\max\left\{100, \frac{P_{CA}(t_d)}{[P_{CA}(t_d)+P_{CB}(t_d)]}\times M_v + P_{CA}(t_d)\right\} \qquad \text{Equation (4.19)}$$

$$P'_{CB}(t_{dd}+1)=\max\left\{100, \frac{P_{CB}(t_d)}{[P_{CA}(t_d)+P_{CB}(t_d)]}\times M_v + P_{CB}(t_d)\right\} \text{ If } P'_{CA}(t_{dd}+1)<100$$

Otherwise $P'_{CB}(t_{dd}+1)=0$ Equation (4.20)

$$P'_{CC}(t_{dd}+1)=100-\{P'_{CA}(t_{dd}+1)+P'_{CB}(t_{dd}+1)\} \qquad \text{Equation (4.21)}$$

$$P'_{CD}(t_{dd}+1)=0 \qquad \text{Equation (4.22)}$$

$$P'_{CF}(t_{dd}+1)=0 \qquad \text{Equation (4.23)}$$

Transition Probabilities from State D to other states

$$P'_{DA}(t_{dd}+1)=\max\left\{100, \frac{P_{DA}(t_d)}{[P_{DA}(t_d)+P_{DB}(t_d)+P_{DC}(t_d)]}\times M_v + P_{DA}(t_d)\right\} \text{Equation (4.24)}$$

$$P'_{DB}(t_{dd}+1)=\max\left\{100,\frac{P_{DB}(t_d)}{[P_{DA}(t_d)+P_{DB}(t_d)+P_{DC}(t_d)]}\times M_v+P_{DB}(t_d)\right\}\text{If}$$

$P'_{DA}(t_{dd}+1)<100$ Otherwise $P'_{DB}(t_{dd}+1)=0$ Equation (4.25)

$$P'_{DC}(t_{dd}+1)=\max\left\{100,\frac{P_{DC}(t_d)}{[P_{DA}(t_d)+P_{DB}(t_d)+P_{DC}(t_d)]}\times M_v+P_{DC}(t_d)\right\}\text{If}$$

$P'_{DA}(t_{dd}+1)+P'_{DB}(t_{dd}+1)<100$ otherwise $P'_{DC}(t_{dd}+1)=0$ Equation (4.26)

$P'_{DD}(t_{dd}+1)=100-\{P'_{DA}(t_{dd}+1)+P'_{DB}(t_{dd}+1)+P'_{DC}(t_{dd}+1)\}$ Equation (4.27)

$P'_{DF}(t_{dd}+1)=0$ Equation (4.28)

Transition Probabilities from State F to other states

$$P'_{FA}(t_{dd}+1)=\max\left\{100,\frac{P_{FA}(t_d)}{[P_{FA}(t_d)+P_{FB}(t_d)+P_{FC}(t_d)+P_{FD}(t_d)]}\times M_v+P_{FA}(t_d)\right\}\quad\text{Equation (4.29)}$$

$$P'_{FB}(t_{dd}+1)=\max\left\{100,\frac{P_{FB}(t_d)}{[P_{FA}(t_d)+P_{FB}(t_d)+P_{FC}(t_d)+P_{FD}(t_d)]}\times M_v+P_{FB}(t_d)\right\}$$

If $P'_{FA}(t_{dd}+1)<100$ otherwise $P'_{FB}(t_{dd}+1)=0$ Equation (4.30)

$$P'_{FC}(t_{dd}+1)=\max\left\{100,\frac{P_{FC}(t_d)}{[P_{FA}(t_d)+P_{FB}(t_d)+P_{FC}(t_d)+P_{FD}(t_d)]}\times M_v+P_{FC}(t_d)\right\}$$

If $P'_{FA}(t_{dd}+1)+P'_{FB}(t_{dd}+1)<100$ otherwise $P'_{FC}(t_{dd}+1)=0$ Equation (4.31)

$$P'_{FD}(t_{dd}+1)=\max\left\{100,\frac{P_{FD}(t_d)}{[P_{FA}(t_d)+P_{FB}(t_d)+P_{FC}(t_d)+P_{FD}(t_d)]}\times M_v+P_{FD}(t_d)\right\}$$

If $P'_{FA}(t_{dd}+1)+P'_{FB}(t_{dd}+1)+P'_{FC}(t_{dd}+1)<100$ otherwise $P'_{FD}(t_{dd}+1)=0$ Equation (4.32)

$P'_{FF}(t_{dd}+1)=100-\{P'_{FA}(t_{dd}+1)+P'_{FB}(t_{dd}+1)+P'_{FC}(t_{dd}+1)+P'_{FD}(t_{dd}+1)\}$ Equation (4.33)

It can be argued that the transition probabilities in the above formulas should not be 100% but have a ceiling on the basis that no single corrective action plan can lead to full certainty in occupying any of the performance states.

If the modification to the transition probability curve will take place at a future time $t_f > t_{dd}$, then the above procedure will still be applicable where $(t_{dd+} 1)$ is replaced by t_f. It should be noted that if there is another impact taking place at a different time t_f, then the revised curve should be again revised using the new value of M_v as outlined in Section 4.8.3. The revised transition probability curve is shown in Figure 4.3.

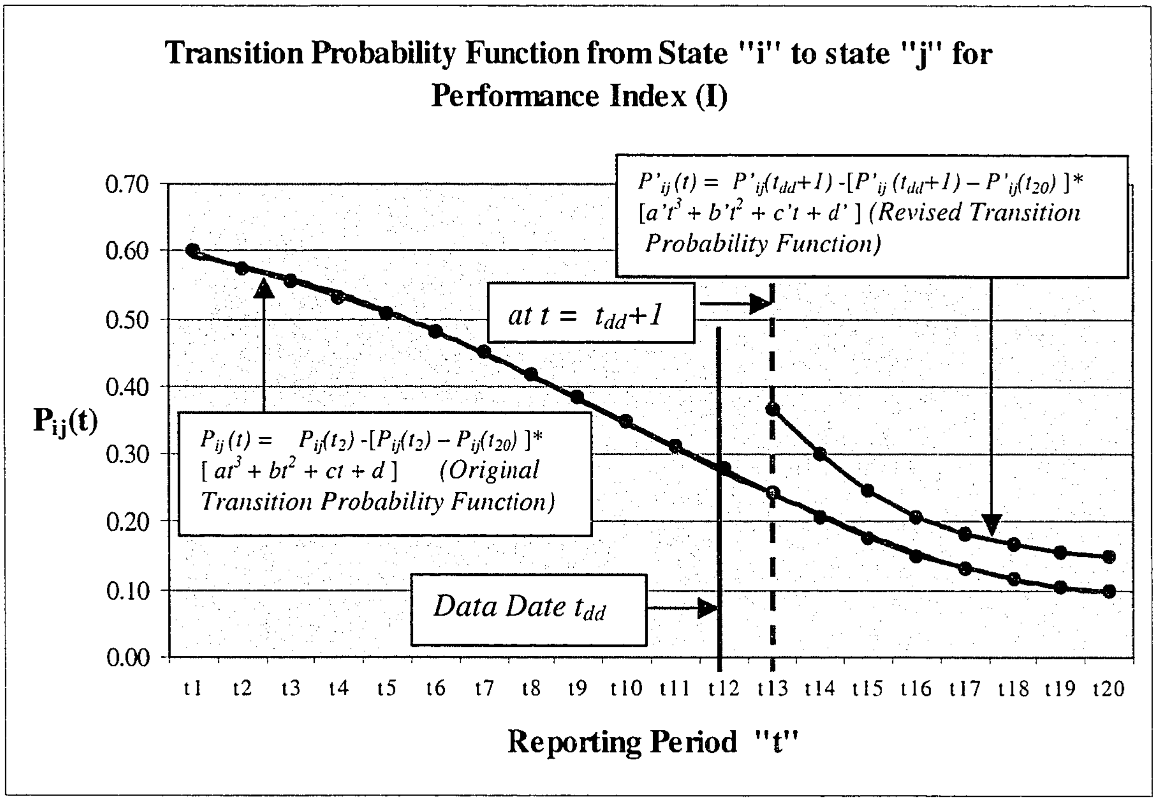


Figure 4. 3 Modified Transition Probability Curve

4.8.5 Overall Objective Function Measurement

In order to determine the fitness value for every chromosome it is required to calculate the objective function for every solution or corrective action plan. Figure 4.4 shows a flowchart outlining the steps to forecast the cost performance index at the end of the project (*i.e.* $t = 20$) using Equation (4.34). The reader is referred to Chapter (3) for further details.

$$CPI_t = \sum_{S=A}^{F} P_S(t) * CPI_S \quad Where \quad t = 20 \ (End\ of\ Project) \qquad \text{Equation (4.34)}$$

$$= P_A(t=20)*CPI_A + P_B(t=20)*CPI_B + P_C(t=20)*CPI_C + P_D(t=20)*CPI_D + P_F(t=20) * CPI_F$$

$$= P_A(t=20) * 1.2 + P_B(t=20) * 1.1 + P_C(t=20) * 1.0 + P_D(t=20) * 0.9 + P_F(t=20) * 0.8.$$

In the above equation, $P_S(t=20)$ for $S = A, B, C, D, \& F$ is the probability that CPI will occupy state "*S*" at the end of project based on the updated probability transition curves.

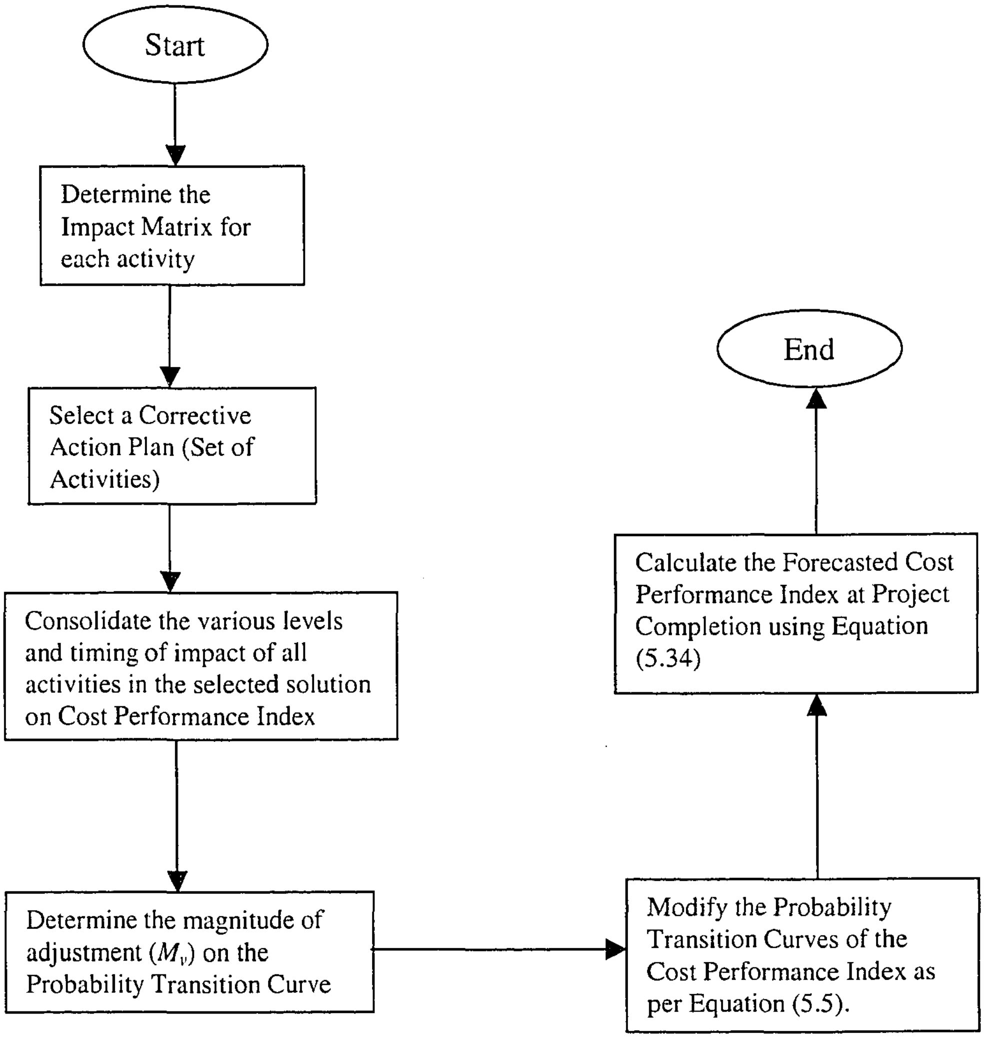


Figure 4. 4 Flowchart to Forecast the Cost Performance Index at Project Completion

Repeating the same procedure for the other seven indices, the overall forecasted project performance at the end of the project could then be obtained by applying Equation (4.35) as follows:

$$PI_T = w_{CPI}(T)\sum_{S=A}^{F} P_S(T) * CPI_S + w_{SPI}(T)\sum_{S=A}^{F} P_S(T) * SPI_S + w_{BPI}(T)\sum_{S=A}^{F} P_S(T) * BPI_S$$

$$+ w_{PPI}(T)\sum_{S=A}^{F} P_S(T) * PPI_S + w_{SFI}(T)\sum_{S=A}^{F} P_S(T) * SFI_S + w_{QPI}(T)\sum_{S=A}^{F} P_S(T) * QPI_S +$$

$$w_{TSI}(T)\sum_{S=A}^{F} P_S(T) * TSI_S + w_{CSI}(T)\sum_{S=A}^{F} P_S(T) * CSI_S \qquad \text{Equation (4.35)}$$

4.9 What makes the performance optimization problem challenging?

Aside from the vast volume of data and the mathematical modeling required by the model, there are some difficulties encountered while solving even simplified performance optimization problems. These challenges are summarized as follows:

4.9.1 Combinatorial Explosion

Since different combinations of possible corrective action activities implemented at different timings can be associated with a corrective action plan, the objective is to select the best combination of activities with best timing and consequently the best corrective action plan. Again the "best" in this sense is the *best-calculated* corrective action plan as per the model. The number of alternatives is very large especially when handling a large number of activities due to the "combinatorial explosion" phenomenon that will be explained in the following sections.

Special Case: Single Activation Times

Denote by C(n,1) as all possible combinations of "*n*" activities where each activity has a single activation period. In the case of single activation time, the set of possible combinations, irrespective of their ordering, are: *1,2,3...n,(1,2),(1,3), ...,(1,n), (2,3),(2,4),..., (1,2,3,..., n).* To prove that $C(n,1) = 2^n - 1$, use the binomial theorem without proof:

$$(x+y)^n = \sum_{j=0}^{n} \binom{n}{j} x^j y^{n-j} \qquad \text{Equation (4.36)}$$

Based on this theorem, the combination quantities $\binom{n}{j}$ noted as $\frac{n!}{j!(n-j)!}$ are called the *binomial coefficients*. Substituting x and y by 1, it can be shown that:

$$\sum_{j=0}^{n} \binom{n}{j} 1^j 1^{n-j} = \sum_{j=0}^{n} \binom{n}{j} = \binom{n}{n} + \binom{n}{n-1} + \binom{n}{n-2} + \dots + \binom{n}{0} = (1+1)^n = 2^n \qquad \text{Equation (4.37)}$$

And thus the number of possible combinations for *n* activities, excluding the "*no action*" plan, is given by:

$$C(n,1) = \sum_{j=1}^{n} \binom{n}{j} = 2^n - 1 \qquad \text{Equation (4.38)}$$

For example if *n=3*, then using Equation (4.38) the total number of combinations is given by:

$$C(3,1) = \sum_{j=1}^{3} \binom{3}{j} = \binom{3}{1} + \binom{3}{2} + \binom{3}{3} = \frac{3!}{1!(3-1)!} + \frac{3!}{2!(3-2)!} + \frac{3!}{3!(3-3)!} = 3 + 3 + 1 = 7 \qquad \text{Equation (4.39)}$$

To demonstrate the phenomenon of "*combinatorial explosion*" let us estimate how many possible combinations, or corrective action plans, we can from 24 activities. Assume that there is 3 possible corrective action activities associated with each of the eight performance areas and can be initiated at only a single point of time. This is equivalent to 24 activities as shown in the *8x3* corrective action decision matrix shown in Table 4.5. This means that the total number of possible combinations, using Equation (4.38), is equal to 2^{24}-1 or around 16.8 millions plans. In some major projects that experience poor performance there can be as many as 40 viable corrective action activities or around one trillion possible scenarios of corrective action plans. One of the GA advantages is its ability to overcome the problem of combinatorial explosion.

Table 4. 5 Corrective Action Matrix with 24 activities

Agent	Corrective Action Activity		
1. Cost	C-01	C-02	C-3
2. Schedule	S-01	S-02	S-3
3. Billing	B-01	B-02	B-3
4. Profitability	P-01	P-02	P-3
5. Safety	F-01	F-02	F-3
6. Quality	Q-01	Q-02	Q-3
7. Team Satisfaction	T-01	T-02	T-3
8. Client Satisfaction	L-01	L-02	L-3

General Case: Multiple Activation Times

Denote by C(n,N$_i$) for $i=1,...,n$, all possible combinations of n activities with each activity i having N_i activation periods. Note the single activation case is a special case where $N_i = 1$ $\forall i \in [1,n]$. In the general optimization case, any single corrective action activity can be initiated within a time range covering multiple periods. The total number of possible combinations can be represented by the following equation.

$$\begin{aligned} C(n,N_i) = & [N_1N_2......N_n] + [N_1N_2......N_{n-1} + ... + N_2N_3......N_n] \\ & + [N_1N_2......N_{n-2} + ... + N_3N_4......N_n] \\ & + [N_1N_2......N_{n-3} + ... + N_4N_5......N_n] \\ & + ... + [N_1 + N_2 + ... + N_n] \end{aligned} \quad \text{Equation (4.40)}$$

The number of terms in the above equation is in the following order:

$$C(n,N_i) = \binom{n}{n} + \binom{n}{1} + \binom{n}{2} + \binom{n}{3} + ... + \binom{n}{n-1} \quad \text{Equation (4.41)}$$

Given $N_1, N_2, \ldots, N_n$ activation periods, and if $\overline{N}_i$ is denoted as the compliment of N_i, then Equation (4.40) can be expressed in the following mathematical form:

$$C(n, N_i) = \prod_{i=1}^{n-0} N_i + \sum_{i_1=1}^{n} \prod_{i_1}^{n-1} \overline{N}_{i_1} + \sum_{i_1,i_2=1}^{n} \prod_{i_1<i_2}^{n-2} \overline{N}_{i_1} \overline{N}_{i_2} + \sum_{i_1,i_2,i_3=1}^{n} \prod_{i_1<i_2<i_3}^{n-3} \overline{N}_{i_1} \overline{N}_{i_2} \overline{N}_{i_3} + \ldots + \sum_{i_1,i_2,\ldots i_{n-1}=1}^{n} \prod_{i_1<i_2<..<i_{n-1}}^{1} \overline{N}_{i_1} \overline{N}_{i_2} .. \overline{N}_{i_{n-1}}$$

Equation (4.42)

Where,

n = number of corrective action activities.

N_i = number of activation periods available for activity i.

The expression $\sum \prod_{i_1<i_2<\ldots<i_j}^{n-j} \overline{N}_{i_1} \overline{N}_{i_2} \ldots \overline{N}_{i_j}$ represents the summation of the many possible combinations of multiplying $(n\text{-}j)$ of N_i's elements. This summation has $\binom{n}{j}$ elements and for mathematical simplicity can be summarized as follows:

$$\sum \prod_{i_1<i_2<\ldots<i_j}^{n-j} \overline{N}_{i_1} \overline{N}_{i_2} \ldots \overline{N}_{i_j} = \sum \prod^{n-j} N \qquad \text{Equation (4.43)}$$

Assuming the above representation is clear to the reader, Equation (4.42) can be reduced to the following form:

$$C(n, N_i) = \sum_{j=0}^{n} \left(\sum \prod^{n-j} N \right) \qquad \text{Equation (4.44)}$$

For example, if the number of activities "n" is only 4, each of which is having 2 activation periods, i.e. $N_1 = N_2 = N_3 = N_4 = 2$, then the total number of combinations as per equation (4.42) is:

$$C(4,2)=\left(N_1\cdot N_2\cdot N_3\cdot N_4\right)+\left(N_2.N_3\cdot N_4+N_1.N_3\cdot N_4+N_1.N_2\cdot N_4+N_1.N_2\cdot N_3\ \right)$$
$$+\left(N_3.N_4+N_2\cdot N_4+N_2.N_3+N_1.N_4+N_1.N_3+N_1.N_2\right)+\left(N_4+N_3+N_2+N_1\right)=16+32+24+8=80$$

It is obvious that the first term in the above expression is equivalent to the first term in equation (4.42) i.e. $\prod_{i=1}^{4} N_i = N_1.\ N_2.\ N_3.\ N_4 = 2^4 = 8$ and the second term is equivalent to

$$\sum_{i_1=1}^{4}\prod_{i_1}^{3}\overline{N}_{i_1} = \left(N_2.N_3\cdot N_4+N_1.N_3\cdot N_4+N_1.N_2\cdot N_4+N_1.N_2\cdot N_3\ \right)= 8+8+8+8 = 32,$$

and so on and so for.

For $N_1,\ldots, N_{n-1}, N_n = 1$, the case of a single activation period, the number of combinations is reduced to 15 as shown below:

$$C(4,1) = 1+4+6+4 = 15\,.$$

Using Equation (4.38) for the single activation case will lead also to 15 possible combinations (2^4-1).

In real life projects we can encounter as many as 40 activities with multiple activation periods. Testing every possibility for this combination would result in trillions of additions. A genetic algorithm can be very useful to find a solution in a relatively short time.

As discussed above, with the large number of possibilities, even for a small number of corrective action activities, a performance optimization model becomes necessary to assist decision-makers to select more effective and better plans that would enhance project performance.

4.9.2 Uncertainty of Corrective Action Activities

In real life applications, finding an improved plan is as critical as coping with the uncertainties and the unpredictable disturbances during the implementation of the plan. Many corrective action plans may be partially executed or completely cancelled due to internal or external reasons.

To handle this issue, the decision maker can associate a probability of occurrence with each corrective action activity. In this case, the impact level can be calculated as follows:

$$\text{Magnitude of Impact} = \text{Likelihood of Activity} \times \text{Impact of Activity} \qquad \text{Equation (4.45)}$$

For example, if a specific corrective action activity, having an impact of $+1L$ at t_{dd+1}, has a 50% chance of occurrence, then the *Magnitude of Impact* is $0.5L$.

4.9.3 Constraints and infeasibility

The optimization model involves setting up the objective function, the constraints, and the decision variables.

Constraints and Objectives

Constraints define the *feasibility* of a corrective action plan and *must* be satisfied. Where as objectives, define the *optimality* of a plan and *should* be satisfied. Both constraints and objectives are related to the performance indices proposed in Chapter 2. A *feasible* plan satisfies all the constraints and an *optimal* plan not only satisfies all the constraints, but also is at least as good as any other feasible plan. At the modeling stage, objectives and constraints are equivalent, but when solving the problem they must be treated differently.

Infeasibility

Depending on the modeling assumptions, there may be no feasible solution to a performance optimization problem. For example, if the profitability performance constraint is set very high or the schedule performance very tight, a feasible solution is not guaranteed. Constraints make the search for an optimal solution more difficult and can break-up the search space.

4.10 Proposed GA Model

As explained above, the objective function and the associated constraints render the optimization problem as non-linear with very large number of variables and cannot be easily handled by classical methods. A GA model can overcome most of the challenges other tools might face and it is able to provide decision makers several equally good alternatives, compared to a single solution by other mathematical or heuristic methods. As a result, GAs, being robust tools, is proposed for optimization. This section describes the proposed solution method for project performance optimization in five parts: (1) formation of the chromosome structure to represent possible solutions to the optimization problem, (2) genetic operators, (3) constraints, (4) fitness measurement to evaluate each string or solution, and (5) performance optimization procedure.

4.10.1 Solution Encoding – Chromosomes

In genetic algorithms a representation scheme is needed to encode solutions to the optimization problem. The *strings* of artificial genetic systems are analogous to *chromosomes* in biological systems (Goldberg 1989). A string or a chromosome represents each individual solution. A chromosome consists of a number of genes arranged in a linear manner as shown in Figure 4.5. Chromosome patterns depend on the problem to be coded. Although much of the early genetic literature used binary representations, genetic algorithms can operate on any data type. In artificial genetic systems there are many alternatives for coding both qualitative and quantitative parameters. In any genetic algorithm, the representation should be a minimal complete expression of a solution to the problem. If a representation contains information more than needed to uniquely identify solutions to the problem, the search space will be larger than necessary and thus makes the search more difficult. Also, infeasible genes should not be part of the genetic representation.

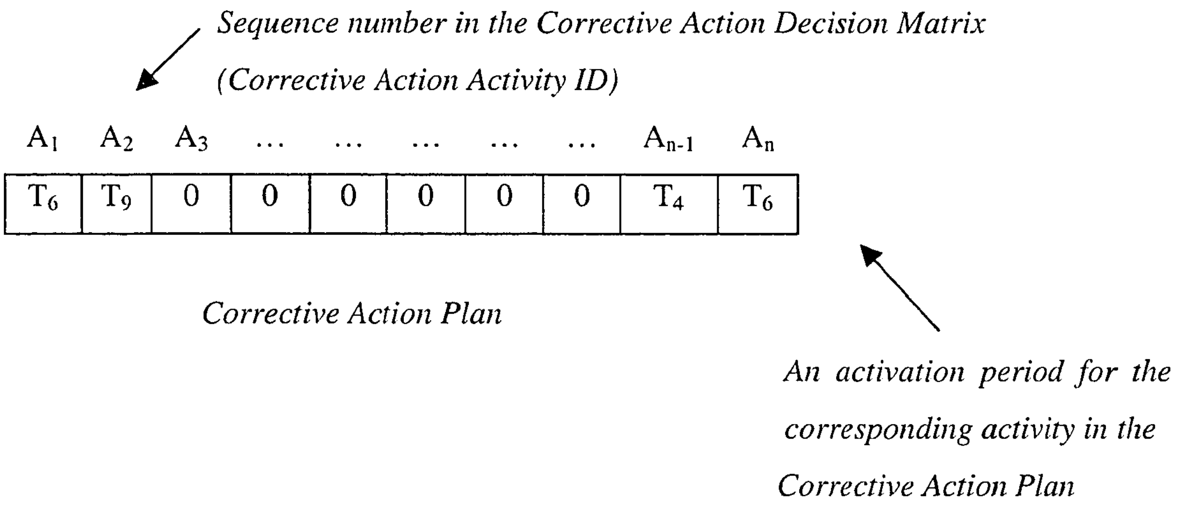


Figure 4. 5 Chromosome Structure

In this study, the representation follows the ordering coding where each gene represents a *corrective action activity* and has two attributes: its *ID* and *activation period.* A solution to the corrective action optimization problem is simply a specific combination of possible corrective action activities with specific activation times. This is what is called the "Optimal Corrective Action Plan". Only activities that are viable or applicable to the project as defined by the decision-maker can take part in the optimization process.

As mentioned earlier, solutions are represented as chromosomes. Figure 4.5 represents a chromosome where each box (gene) in the string corresponds to an activity and each string represents a solution or a *corrective action plan.* There are as many active genes in the string as there are *activities* within a *corrective action plan.* In other words, a string can vary from one gene (plan consisting of one activity) to "*n*" genes (plan including all possible "*n*" activities). In both cases, the length of the string is "*n*" genes but in the first case there will be only one active gene or (n-1) idle genes and in the latter case "*n*" active genes with no idle genes. In this simple mapping of corrective action activity to gene position, the first activity in the matrix would occupy the first gene position and the second activity is mapped to the second gene and so on. The sequence of activities in the chromosome corresponds to the sequence of activities in the corrective action decision matrix shown in Table 4.1. In Figure 4.5, "*Activity ID*" denotes each gene's corresponding corrective action activity. The content of the box corresponds to the time of activation of the associated activity. Therefore, each solution is defined by a certain set of gene values in the chromosome and the chromosome structure is designed so that all permutations can be represented and evaluated.

For example, Figure 4.5 represents a corrective action plan (solution) consisting of four activities namely, A_1, A_2, A_{n-1}, *and* A_n with activation times of T_6, T_9, T_4, *and* T_6 respectively. The remaining activities namely A_3,....,A_{n-2} have a gene values of zero or with no activation times and consequently not part of the solution.

Gene Length and Performance

As shown above, the size of the corrective action decision matrix is directly related to the length of the chromosome string. Because the string length and the associated combinatorial explosion greatly impact the performance of the GA algorithm, the decision matrix should only include meaningful and feasible corrective action activities. The decision maker should exclude any infeasible or non-viable options.

4.10.2 Genetic Operators

The following is a brief description of the various genetic operators that could have great impact on the functionality of the optimization model.

Selection or Reproduction Operator

This is usually the first operator to be applied on a population. The goal of the reproduction process is to enable the strings with good fitness values to survive into the next generation. It selects an above average string in a population in order to perform the crossover operation. Copying chromosomes based on their fitness values implies that chromosomes with a higher fitness value have a higher probability of contributing off springs in the next generation (Goldberg 1989). There are many types of reproduction operators in the GA literature. The *roulette* selection operator is the classical and most common selection method used by GAs. This method selects a string for mating with a probability proportional to its fitness. As such, reproduction does not alter the genes of the parent strings. Each string in the population is associated with a selection probability that can be determined using Equation (4.46).

$$p_j = \frac{f_j}{\sum_{j=1}^{s} f_j} \qquad \text{Equation (4.46)}$$

Where:

p_j is the selection probability of string or plan j.

f_j is the fitness value of string or plan j, and

s is the population size.

Several researchers suggested a number of selection techniques in order to reduce the stochastic errors associated with the roulette wheel selection method (Goldberg 1989). For example, Brindle's dissertation (1981) presented six different selection schemes. In all schemes, the impact of reproduction on the number of schemata is that above-average schemata grow and below-average schemata die off.

Crossover Operator

Crossover is a structured yet random information exchange between two strings. It is performed by randomly selecting two solutions from the population and exchanging their genes information. Crossover is carried out at a probability (P_c) and the chromosomes that are not selected for crossover remain unchanged and copied into the next generation. Thus, the total number of chromosomes within a population remains constant during the entire GA operation. There are many types of crossover techniques, for example, single-point crossover involves exchanging of a part of each solution in a pair at a randomly selected point. The aim of all crossover techniques is to arrange for good schemas (partial solutions or subset of strings) present in different chromosomes to combine and form a single solution. Figure 4.6 illustrates the crossover operation where two parent strings are randomly selected and broken at a random point (gene 3). After the exchange of genetic information, 2 new strings are generated (offspring A and offspring B). There is also a possibility that this genetic operator will negatively impact the quality of an existing good solution especially the long ones (Goldberg 1989).

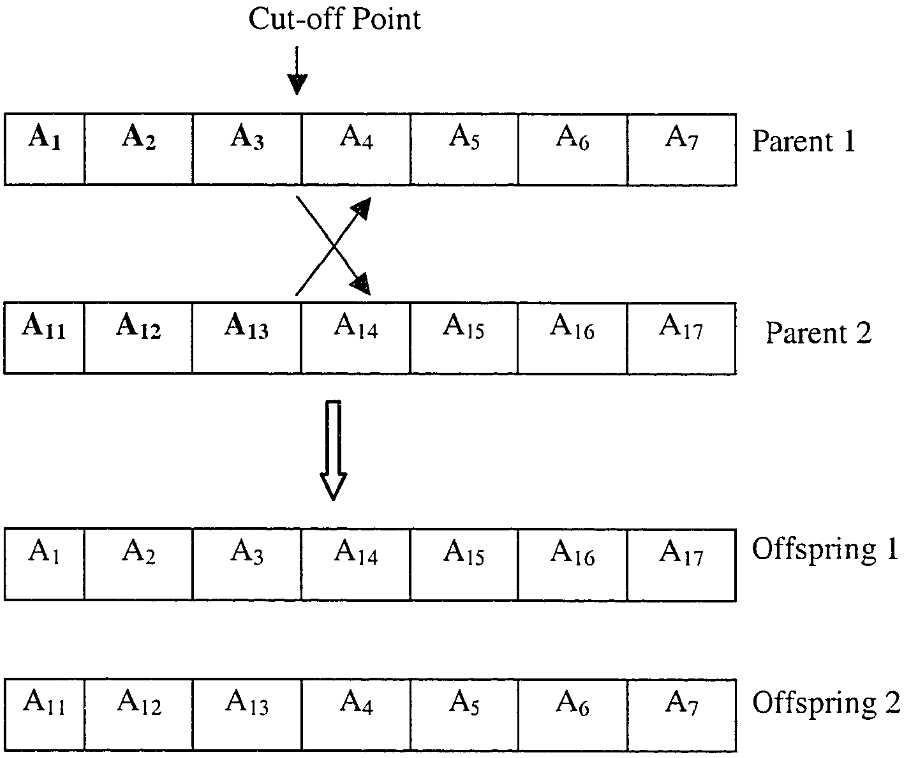


Figure 4. 6 Simple Crossover Operation

Mutation

Mutation usually follows crossover and adds new information by changing the genes' values within a chromosome in a random manner. The main objective of mutation is to improve genetic diversity by restoring lost genetic information or exploring new areas to prevent the GA from getting trapped in a local optimum and converging to sub-optimal solutions. By itself, mutation is a random walk through the string space (Goldberg 1989). It is carried out after the creation of the new population in order to ensure that the new chromosomes are not uniform (Goldberg 1989). The goal is to create a solution in the neighborhood of the current solution to conduct a local search around the current point. If the mutation operation is not applied, some possibly significant regions of the search space may never be explored. It should be noted that not every gene should be mutated and the rate or probability of mutation (P_m) is related to the size of the population and is often kept very low in order not to distort the good chromosomes. The value ranges of (P_c) and (P_m) is normally [0.5-1.0] and [0.001-0.05] respectively (Li and Love 1997). *Swap mutation* is one type of mutation where two randomly selected genes are simply swapped as shown in Figure 4.7. Another type of mutation is where the whole sequence of activities (or at least part of the string) is reversed. For example, after the operation, a chromosome (A_1, A_2, A_3, A_4, A_5, A_6, A_7) with activity starting dates (T_7, T_2, T_5, T_5, T_1, T_8, T_2) will have starting dates as (T_2, T_8, T_1, T_5, T_5, T_2, T_7). Note that the timing of the activities will be reversed and not the activity ID's.

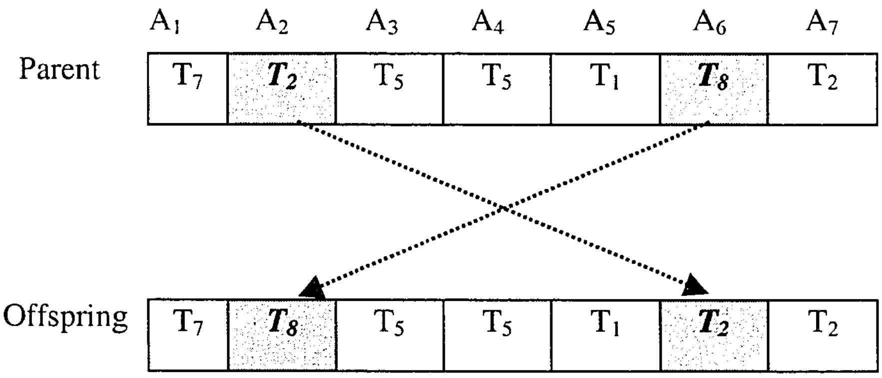


Figure 4. 7 Swap Mutation Operation

The GA literature shows that the performance of the genetic algorithm is greatly dependent on the genetic operators. For example, if the crossover operator rate is very low, the algorithm will fail. If the mutation rate is too high, the algorithm will perform only as well as a random search.

Schema Theorem

The Schema Theorem is widely accepted to be the foundation for explanations of the power of genetic algorithms (GAs). The Schema Theorem, or the Fundamental Theorem of Genetic Algorithms, developed by John Holland (Holland 1975), states that short, low-order, above average schemata receive exponentially increasing trials in subsequent generations. In other words, schemata with fitness values above the population average will receive an increasing number of samples in the next generation (Goldberg 1989).

4.10.3 Constraints

The degree of feasibility varies from one project to another and depends upon the project objectives and the performance constraints set up by the project management team. To assist the optimization process in finding the best combination of corrective action activities, two types of constraints are incorporated into the model to reduce the solution space:

1. **Hard constraints**: These constraints cannot be violated or relaxed because it will jeopardize the company objectives and values. Safety performance in accordance with a corporate "zero harm" policy is a typical hard constraint. The Schedule performance at the end of the project can be another hard constraint if the contract stipulates high liquidated damages.

2. **Soft constraints**: These constraints can be relaxed to some degree but at the expense of the project performance. Cost performance can be a soft constraint and may be relaxed to satisfy some other hard constraints.

The model does not impose the type of constraints but are left for the decision maker to specify. As a constrained problem, the performance optimization problem is formulated to maximize the project performance index at the end of project PI_T subject to the following inequality constraints:

$$I_T \geq I_C \qquad I = CPI, SPI, BPI, PPI, SFI, QPI, TSI, CSI \qquad \text{Equation (4.47)}$$

Where,

I_T is the performance index value at time "T" i.e. end of the project, and
I_C is the critical or threshold value of index (I) at $t = T$.

For a solution to be feasible it must satisfy all the above constraints. If the optimization problem is infeasible, the decision maker should either consider other corrective courses of action or release the constraints or both. In general, infeasible solutions have no fitness, but the performance optimization problem at hand can be a highly constrained one. In this case, identifying a feasible corrective action plan can be as difficult as locating the optimal. To get some information out of infeasible solutions, they must be given credit or fitness value that is a function of the degree of constraint violation. This can be accomplished by using a *penalty method* (Goldberg 1989) as will be explained in the next section.

4.10.4 Fitness Measurement

As mentioned earlier, GAs use the survival of the fittest principle to conduct a search process and consequently are naturally suited to solve maximization problems. Also as described above, GAs can directly solve only unconstrained optimization problems since the GA model does not consider any constraints. The constrained performance optimization problem must be converted into an unconstrained problem. This can be achieved by incorporating a penalty function to the fitness function of the genetic algorithm. A fitness function that returns a numerical fitness value must be developed for each problem. The fitness of each chromosome is measured by the performance of the decision variables as defined by the objective function and the related constraints. In other words, the fitness is a function of two parts: a constraint satisfaction part (f_c) and an objective performance part (f_o) (Wall 1996). Since any corrective action plan is not viable if any of the constraints is not met, the objective fitness is not considered until all the constraints have been satisfied. This means that the objective function is penalized whenever any of the constraints are violated. In this research, the fitness of each chromosome is proposed to be a composite score of two measures of fitness, the constraint fitness and the objective fitness. For a plan j, with a constraint fitness (f_c) and an objective performance fitness (f_o), the overall fitness value (f_j) can be determined as follows:

$$f_j = \begin{cases} \frac{f_{constraints}}{2} = \frac{f_c}{2} & \text{If at least one of the constraints is violated } (f_c < 1.0). \\ \frac{f_{objective} + f_{constraints}}{2} = \frac{f_o + f_c}{2} & \text{If all constraints are satisfied } (f_c = 1.0). \end{cases}$$

Equation (4.48)

Constraint Satisfaction

Every proposed corrective action plan should satisfy multiple constraints, where each constraint measures some aspect of the feasibility of the plan.

In the above Equation (4.48), f_c, the composite fitness value of the constraints part, is determined as follows:

$$f_c = \sum_{i=1}^{8} w_i * f_i \qquad \text{Equation (4.49)}$$

Where:

w_i is the weight or relative significance of constraint i, as determined by the user, and

f_i is the performance of constraint i, which is inversely proportional to the violation (V_i) as measured by the deviation from the threshold value (T_i). If F_i is the forecasted value, then $V_i = |T_i - F_i|$.

Based on above, f_i is calculated by the following formula:

$$f_i = \begin{cases} \dfrac{1}{1+(T_i - F_i)} & \text{If the constraint is violated } (T_i > F_i) \\ 1 & \text{If the constraint is satisfied } (T_i <= F_i) \end{cases} \qquad \text{Equation (4.50)}$$

The various constraint fitness values are weighted to indicate the different levels of significance between constraints. For example, the safety constraint may be given more importance than the schedule constraint in some projects. On the other hand, it can be argued that all constraints must be satisfied before optimality is considered and thus equal weights can be assigned to the constraints. In this research it is proposed that the decision makers will choose the weights using the AHP methodology explained in Chapter 2.

Using composite scores to measure fitness of solutions will enable the partially feasible plans to receive some credit. Some plans may be infeasible but they may contain many feasible activities. If a plan does not meet all the constraints it is given a score of "0". In in this case, there will be no feedback to the GA about the value of one infeasible plan over another. Using the proposed scale for measuring infeasible solutions, the genetic algorithm can evolve plans that are more feasible and may eventually locate completely feasible solutions.

Objective Performance Fitness

As discussed in Chapter 2, every construction project has many multiple, and in most cases conflicting, objectives. Each objective was normalized and were all weighted to form the overall project performance objective (***PI***) which is equivalent to $f_{o,}$ the fitness value of the objective function. In this case (***PI***) is the overall project performance forecasted at the end of the project (t= T) and is determined as follows:

$$f_o = PI_T = w_{CPI}(T)\sum_{S=A}^{F} P_S(T) * CPI_S + w_{SPI}(T)\sum_{S=A}^{F} P_S(T) * SPI_S + w_{BPI}(T)\sum_{S=A}^{F} P_S(T) * BPI_S + w_{PPI}(T)\sum_{S=A}^{F} P_S(T) * PPI_S + w_{SFI}(T)\sum_{S=A}^{F} P_S(T) * SFI_S + w_{QPI}(T)\sum_{S=A}^{F} P_S(T) * QPI_S + w_{TSI}(T)\sum_{S=A}^{F} P_S(T) * TSI_S + w_{CSI}(T)\sum_{S=A}^{F} P_S(T) * CSI_S \qquad \text{Equation (4.51)}$$

The reader is referred to Chapter 3 for a complete derivation of the above formula.

If the maximum project performance index as determined by Equation (4.51) is ***M***, then using Equation (4.48), the score for each string, or plan, can range from 0 to *(1+M)*/2. Any plan with a score of less than 0.5 does not satisfy all of the eight constraints and hence is not feasible. Any plan with a score of greater than 1.0 not only satisfies all the constraints but will also lead to above target overall performance at the end of the project.

Treating objectives and constraints separately will enable the Genetic Algorithm to distinguish between feasible and infeasible solutions. If a single fitness figure can represent both a feasible solution with poor objective performance and an infeasible solution with good objective performance, the genetic algorithm may be deceived and can select infeasible solutions with high objective performance scores.

In order for infeasible solutions not to dominate the evolution process, the threshold value before considering objectives is very critical and is proposed in this work to be 0.5. It should be noted that by giving infeasible solutions a measure of fitness of less than 0.5 instead of neglecting them, the solutions are given an opportunity to participate in the evolution process and are not wasted, while ensuring that feasible solutions are granted higher priorities. For example, a corrective action plan that satisfies all the constraints except the scheduling constraint and will contribute to project performance should not be neglected but given a chance to participate in the fitness competition.

Termination Criteria

Genetic algorithms can operate for an infinite period of time until some termination conditions are satisfied. Some of the widely used termination criteria are maximum number of generations and convergence rate of the population.

Scaling Problem

As shown above, the probability of reproduction is directly proportional to the fitness value of each solution. It was also explained that the fitness value is a function of the objective function, which is an index, and its numerical value can roughly range from 0 to 1.5. At the start of the GA run, and if left to the normal selection rule as per Equation (4.46), the super chromosomes would take over a major proportion of the finite population in a single generation and will lead to premature convergence, an undesirable end (Goldberg 1989). In this case, the fitness values must be scaled back to prevent takeover by the super strings. Towards the end of the run, the differences between the fitness values decrease and the population average fitness gets close to the population best fitness. Without scaling, the best chromosomes will get quite the same probability as the other solutions and the genetic algorithm stops progressing. Here, the fitness values must be scaled up to highlight the differences between the solutions.

In both cases, at the start and end of the run, fitness scaling can help. Scaling helps prevent the early domination of *Super* strings and at later stages encourages a constructive competition among near equal fitness solutions. The GA literature contains many scaling mechanisms. For example, Gillies (1985) proposed a power law form of scaling where the scaled fitness f' is obtained by raising the raw fitness f to a specified power k as shown in Equation (4.52).

$$f' = f^k \qquad \text{Equation (4.52)}$$

4.10.5 Optimization Procedure

The user is required to enter the "GAs Parameters" which includes: 1-number of generations, 2-population Size, 3- crossover Rate, and 4- mutation Rate. When the input is complete, the module will be ready to process the data and select the optimal or near optimal plans that would lead to the *best-computed* performance at the end of the project.

The overall GA corrective action optimization procedure is summarized in Figure 4.8. The process starts with a set of encoded chromosomes or solutions that are randomly generated to form an initial population. It should be emphasized that GAs work with a population of solutions rather than with a single one. Each individual solution passes through the process of evaluation, selection and recombination in cycles called generations. The GA evolves the solutions over many generations until a terminating condition is met.

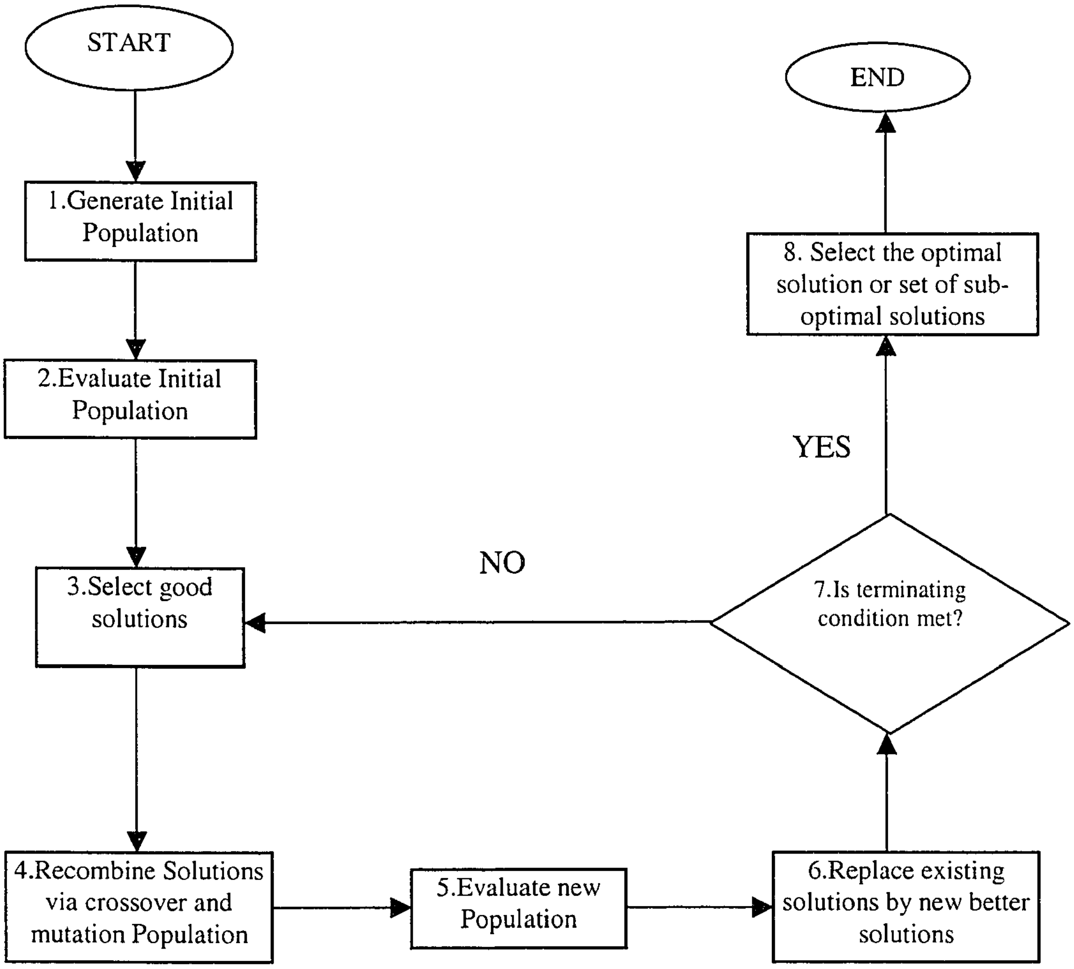


Figure 4. 8 Proposed GA Optimization Flow chart

The following steps outline the procedure:

1. Form an initial population of solutions.

2. Evaluate each individual solution by calculating its fitness value in accordance with the fitness measurement guidelines explained above. The level of fitness will impact its chances of being selected for recombination. The objective is to maximize fitness by maximizing project performance of feasible solutions. The higher the fitness of a certain solution the more desirable it is. The calculated fitness measures can be stored in database in order to avoid repeating the exercise for the same chromosomes appearing in future generations.

3. Select solutions for recombination. The higher the fitness of a solution, the higher probability it has of being selected for recombination. The algorithm selects the fittest strings as parents, and the above average strings will have more offspring in the next generation.

4. Recombine solutions via crossover and mutation. The crossover operation combines genetic material from two parents to form new solutions. Random mutation is applied to promote diversity and is meant to modify only a small fraction of the strings.

5. Evaluate the fitness of the new population.

6. Replace existing solutions with new fitter chromosomes to establish a new generation. It should be noted that the offsprings do not replace the parent strings; instead they replace strings with low fitness values that are discarded at each generation so that the population size remains constant.

7. If the number of generations is met go to step 8, otherwise go to step 3. It should be noted that after a number of generations, the population evolves to an optimal or near optimal solution.

8. Determine the optimal *(computed)* solution or a set of near optimal plans in the current population.

It should be emphasized that the optimal solution proposed by the GA module is not necessarily the best solution, since it is a function of the available information and user's input. It should also be noted that near-optimal solutions could exist in the final pool of solutions that may be more desirable and applicable when other practical considerations are factored in.

Based on above, the GA model will propose not only the optimal solution but also a set of near optimal solutions. Again, the *computed optimal* solutions offered by the GA model are not necessarily the *best* course of action. This is due to the fact that in construction performance management there are many interdependent internal and external (client related) qualitative factors that are not easy to quantify or model but can have significant impact on the decision taken. A sound plan must be augmented by an expert assessment. The proposed tool will only *assist* the decision-maker select a *better or improved* course of action and is never intended to completely replace human judgment.

4.11 Possible enhancements to the GA Model

The following recommendations can enhance the performance of the GA model and need to be evaluated. Problem-specific knowledge may be used to make the search for good solutions more intelligent and faster.

4.11.1 Tuning the Genetic Algorithm

Since the objective of this research is to develop an optimization framework using GA methodology, a computer model was not built and experimental results were not obtained. As a result, no specific attempt was made to tune the genetic algorithm. Tuning the genetic algorithm is necessary in order to evaluate the impact of the GA parameters on the computational time and optimize the model performance. Proper selection of genetic representation and genetic operators is critical to the performance of a genetic algorithm. The representation determines the search space boundaries, and the operators determine how the space can be traversed. The model should be run for different population sizes, crossover and mutation types and probabilities, and number of generations. Small changes to the genetic operators can have significant impact on the algorithm's performance. For example, the population size and number of generations affect the processing time because the fitness value must be calculated for every chromosome in every generation. Future research should be carried to establish these GA parameters although there are some rules of thumb. The final architecture of the model will be arrived at only after many cycles of experimentation and re-design. Comparison with other heuristic methods using various project sizes to validate the performance of the GA model can also be part of future research.

4.11.2 Integration of the GA algorithm with Expert Systems

As mentioned earlier, the indifference of GAs toward problem-specific information is a major advantage. On the other hand, not using all the knowledge available in a particular problem puts GAs at a competitive disadvantage with techniques that make use of this knowledge (Goldberg 1989).

One of the promising future research areas is the integration of the proposed GA optimization model with knowledge-based Systems like TRAC-based expert system. TRAC is *Techniques for Resolving Performance Contradictions* and will be introduced and explained in Chapter 5 as part of related future research. An expert system can be utilized to: (1) form the initial population of solutions; (2) minimize conflicts among competing plans; (3) handle constraints and (4) construct boundaries for the GA search space. It is very advantageous to consider such a hybrid system for the performance optimization problem at hand because it speeds up the genetic algorithm search. A number of authors developed hybrid systems like Cheng and Ko (2003) and Kim et al. (2004) who combined neural networks with GAs.

4.11.3 Knowledge-Augmented Operators and Approximate Function Evaluation Methods

In addition to the hybrid techniques, the problem-specific information can be used to guide the genetic operators, like crossover and mutation, towards better solutions (Goldberg 1989). The optimization model discussed above reveals a costly and complex objective function evaluation process as it involves many layers of subroutines and computations. Less accurate approximations to the objective function can lead to savings in computation time given the fact that GAs behave robustly under error because of their population sampling approach (Goldberg 1989). On the other hand, the use of micro-operators like dominance, inversion, and duplication and macro-operators like niche, marriage restriction, and migration may advance the GA search and need to be investigated.

4.12 Conclusion

Construction performance optimization is a large-scale and complex problem. The existing heuristic and mathematical programming methods are not efficient for modeling and solving real-life problems. This research shows that GAs are an efficient and effective technique for constrained project performance optimization.

This research presented a general GA framework for project performance optimization throughout the project construction phase considering all objectives, constraints and available corrective measures. It extends the capabilities of the forecasting model proposed in Chapter 3 to include corrective action selection and optimization using genetic algorithms, and consequently it closes the cycle of total project controls.

The model utilized the project goals structure and performance forecasting model presented in Chapters 2 and 3 respectively. The model will assist decision makers by proposing a set of *effective* corrective action plans that are not necessarily the *best* plans (when other qualitative factors are considered). In many cases, decision makers will modify the plans, proposed by the model, to generate better plans when other external factors are considered. The real objective of the optimization model is to propose improved solutions to assist users in taking more informed and timely decisions. This approach provides construction managers with a new way of selecting and evaluating corrective action plans in a more systematic manner. Also, the model enables the user to carry out what-if scenarios to assess the impact of a specific plan on the final project performance.

The proposed model has a few limitations that could be improved. It requires the decision-makers to input the viable corrective action activities, activation periods and the corresponding impact on the various aspects of performance. In addition, the model requires the decision-makers to determine the best and most viable corrective action plan (or multiple plans) from a pool of optimal and near-optimal plans. As a single decision-maker may not have all the data to support his selection, a decision support system is highly desirable to assist this decision-maker in selecting the right plan. Although GAs share one drawback with heuristic methods because it is not possible to know if an optimal (*computed*) solution has been obtained. From the practical application viewpoint, near optimal solutions may provide sufficient information for construction management decision making.

Future research should be directed towards developing a computer prototype using computer languages like *Visual Basic* for tuning the GA optimization tool and testing with real-world problems. Functional full-scale systems will be of great help to practitioners and can be used as a decision support system by construction contractors. However, their implementation is a very challenging task especially when applied to projects with large space searches.

REFERENCES

Al-.Tabtabai, H. M., and Alex, A.P., (1997). "Manpower Scheduling Optimization Using Genetic Algorithms." *Proceedings of the Fourth congress on Computing in Civil Engineering*, Philadelphia, June 1997, 702-709.

Brindle, A., (1981). *Genetic algorithms for function optimization*, Doctoral dissertation, University of Alberta, Edmonton.

Bush, V.G., (1973). *Construction management: A handbook for contractors, architects, and students*, Reston, Va.

Chau, K. W., (2004). "A two-stage dynamic model on allocation of construction facilities with genetic algorithm." *Automation in Construction*, 13(4), 481-490.

Chan, Weng-Tat, Chua, David K. H., and Kannan, Govindan, (1996). "Construction Resource Scheduling with Genetic Algorithms." *Journal of Construction Engineering and Management*, ASCE, 122 (2), 125-132.

Cheng, Min-Yuan, and Ko, Chien-Ho, (2003). "Object-Oriented Evolutionary Fuzzy Neural Inference System for Construction Management." *Journal of Construction Engineering and Management*, ASCE, 129(4), 461-469.

Diekmann, J.E., and Al-Tabtabai, H., (1992). "Knowledge-Based Approach to Construction Project Control." *International Journal of Project Management*, 10(1), 23-30.

Feng, Chung-Wei, Cheng, Tao-Ming, and Wu, Hsien-Tang, (2004). "Optimizing the schedule of dispatching RMC trucks through genetic algorithms." *Automation in Construction*, 13(3), 327-340.

Feng, Chung-Wei, Liu, Liang, and Burns, Scott A., (1997). "Using Genetic Algorithms to Solve Construction Time-Cost Trade-Off Problems." *Journal of Construction Engineering and Management*, ASCE, 11(3), 184-189.

Gen, M., and Cheng, R., (1997). *Genetic algorithms and engineering design*, Wiley, New York.

Gillies, A. M., (1985). *Machine learning procedures for generating image domain features detectors*, Doctoral dissertation, University of Michigan, Ann Arbor.

Goldberg, D. E., (1989). *Genetic algorithms in search, optimization, and machine learning*, Addison-Wesley, Reading, Mass.

Hegazy, Tarek, and Kassab, Moustafa, (2003). "Resource Optimization Using Combined Simulation and Genetic Algorithms." *Journal of Construction Engineering and Management*, ASCE, 129(6), 698-705.

Hegazy, Tarek, and Petzold, Kevin, (2003). "Genetic Optimization for Dynamic Project Control." *Journal of Construction Engineering and Management*, ASCE, 129(4), 396-404.

Hegazy, Tarek, and Wassef, Nagib, (2001). "Cost Optimization in Projects with Repetitive Nonserial Activities." *Journal of Construction Engineering and Management*, ASCE, 127(3), 183-191.

Hegazy, Tarek, Elhakeem, Ahmed, and Elbeltagi, Emad, (2004). "Distributed Scheduling Model for Infrastructure Networks." *Journal of Construction Engineering and Management*, ASCE, 130(2), 160-167.

Holland, J. H., (1975). *Adaptation in natural and artificial systems*, The University of Michigan Press, Ann Arbor.

Kim, Gwang-Hee, Yoon, Jie-Eon, An, Sung-Hoon, Cho, Hun-Hee, and Kang, Kyung-In, (2004). "Neural network model incorporating a genetic algorithm in estimating construction costs." *Building and Environment*, 39(11), 1333-1340.

Leu, Sou-Sen, and Yang, Chung-Huei, (1999). "GA-Based Multicriteria Optimal Model For Construction Scheduling." *Journal of Construction Engineering and Management*, ASCE, 125(6), 420-427.

Leu, Sou-Sen, Chen, An-Ting, and Yang, Chung-Huei, (2001). "A GA-based fuzzy optimal model for construction time-cost trade-off." *International Journal of Project Management*, 19(1), 47-58.

Li, Heng and Love, Peter E. D., (1998). "Site-Level Facilities Layout Using Genetic Algorithms." *Journal of Computing in Civil Engineering*, ASCE, 12(4), 227-231.

Li, Heng, and Love, Peter, (1997). "Using Improved Genetic Algorithms to Facilitate Time-Cost Optimization." *Journal of Construction Engineering and Management*, ASCE, 123(3), 233-237.

Marzouk, Mohamed, and Moselhi, Osama, (2004). "Multiobjective Optimization of Earthmoving Operations." *Journal of Construction Engineering and Management*, ASCE, 130(1), 105-113.

Mawdesley, Michael J., Al-Jibouri, Saad H., and Yang, Hongbo, (2002). "Genetic Algorithms for Construction Site Layout in Project Planning." *Journal of Construction Engineering and Management*, ASCE, 128(5), 418-426.

Que, Bryan Christopher, (2002). "Incorporating Practicability into Genetic Algorithm-Based Time-Cost Optimization." *Journal of Construction Engineering and Management*, ASCE, 128 (2), 139-143.

Senouci, Ahmed B., and Eldin, Neil N., (2004). "Use of Genetic Algorithms in Resource Scheduling of Construction Projects." *Journal of Construction Engineering and Management*, ASCE, 130 (6), 869-877.

Wall, Mattew Bartschi, (1996). *A Genetic Algorithm for Resource-Constrained Scheduling*, Doctoral Dissertation, MIT.

Zheng, Daisy X. M., Ng, S. Thomas, and Kumaraswamy, Mohan M., (2004). "Applying a Genetic Algorithm-Based Multiobjective Approach for Time-Cost Optimization." *Journal of Construction Engineering and Management*, ASCE, 130(2), 168-176.

Zheng, Daisy X. M., Ng, S. Thomas, and Kumaraswamy, Mohan M., (2003). "GA-Based Multiobjective Technique for Multi-Resource Leveling." *Proceedings of the Construction Research Congress*, ASCE, March 2003.

5.1 Introduction to Techniques for Resolving Project Performance Contradictions (TRAC)

5.1.1 Introduction

Improving the overall project performance has always been emphasized in construction projects. When project objectives contradict, the project manager must apply mitigating or conflict resolution strategies to remove or minimize the level of contradiction. A typical example of conflict is between cost and schedule performance, because if schedule is crashed then cost tends to increase. Practically, a project manager uses his construction expertise and judgment to analyze contradictions and minimize project performance deviations. Most of the present project controls systems are only designed to measure performance and highlight deviations from the baseline. Although some of these systems attempt to diagnose the root cause of the deviations and suggest corrective action, none is designed to resolve conflicts in a systematic manner to improve the overall project performance. In practice, some project managers avoid using creative thinking when attempting to resolve conflict and propose corrective action. This is due to the fact that they view innovative and creative solutions could increase the risk of project failure. The purpose of this chapter is to present a new approach to resolve conflicts between the eight competing performance indices discussed in chapter 2. This innovative approach uses the TRIZ concept to develop the framework of a conflict resolution strategy called (TRAC), or the Techniques for Resolving Performance Contradictions.

This section attempts to explore the applicability of the 40 Inventive Principles of the innovative TRIZ theory, developed by Genrich Altshuller, in the field of construction performance and management. This approach comes in the wake of a need to eliminate or minimize the contradiction between the competing performance indices and a need to propose corrective action plans in a timely and systematic manner that lead to less conflict and higher project performance. Selection of effective plans can be improved by developing some kind of orderly search process with rules.

This study aims also to shed light on the concept of performance contradictions and the significance of conflicts among the competing project attributes. It attempts to develop an algorithmic approach for solving project performance contradictions. The objective of this methodology is to avoid or al least minimize *performance tradeoffs* and achieve what is called a win-win situation. A *performance tradeoff* is a situation where if one performance index improves, some other index (or indices) deteriorates.

5.1.2 Resolving performance problems among conflicting indices

The ability to identify and resolve performance problems is extremely important for project managers, construction managers, and others who are involved in taking corrective action for the project to achieve its planned goals. A performance problem is a gap (usually negative) between the actual status and the planned or target baseline established by management. The conflict resolution process itself depends on the ability and skills of a project manager. Two construction managers with different knowledge will propose different corrective action plans to solve the same performance problem. For difficult problems, the some project managers may not know all possible corrective action scenarios.

5.1.2.1 Conflict and Interdependency among Project Objectives

Conflicts and contradictions occur when improving one project object or one performance index (e.g. cost) negatively affects one or more other indices (e.g. schedule and profitability). Performance conflict will impact the overall project performance if not resolved. In any project environment, conflicts among objectives are inevitable. However, conflicts and their resolution can be planned for, as will be explained later on. TRAC focuses on the systematic use of project and construction management principles to minimize the impact of conflicting corrective action decisions on project performance. In many cases it is not possible to satisfy all project objectives. In this case, establishing priorities for project objectives by the company management can reduce conflict. Yet even with priority establishment, conflicts still develop due to the contradictory nature of the many objectives in a single project. The negative results of these conflicts on the overall project performance can be minimized if the project manager can understand their composition and manage their impact. This research presents a conflict resolution guide to help the project manager to more effectively manage conflict among his/her project objectives.

Any process for managing performance should recognize that even the smallest change in a project could easily affect all the project's objectives. For example, time and cost are inter-related especially in labor-intensive projects and as cost increases profitability decreases. As the schedule slips, costs tend to increase. Also when the schedule is crashed quality tends to decrease.

5.1.2.2 Corrective Action Plans in Construction

As discussed in Chapter One, corrective action selection and implementation is a primary task within the project controls cycle. A corrective action plan is a set of activities, selected and implemented by the project team, to get the project back on track. Some project managers tend to focus on suggesting corrective action without considering its adverse impact on the various aspects of performance. In other words, corrective actions are not designed on the basis of knowledge of the existing conflict between the performance attributes of the project. This study aims to assist, especially the less experienced project manager, develop viable and applicable corrective action plans.

5.1.2.3 Classical Methods for resolving conflicts

The *trial and error* method is the oldest and still the most popular method for problem solving within the construction industry. This method is based on irregular search of the problem's solution space and works well for simple and small construction projects where the corrective action alternatives are limited. Unfortunately, most construction projects are complicated and attempts to use the trial-and-error method to locate corrective action activities will have high chance of failure. The drawbacks of this method can be summarized as follows:

- The trial-and-error method is a time-consuming process and its efficiency in resolving conflicts is low as there is no mechanism to search for and assess the impact of all possible plans. Knowing that timely corrective action is of utmost importance in today's competitive environment.
- This method follows the project manager's own search direction, and if not very experienced, it probably keeps him from the right solution. Many solutions may reside in construction or project management areas that are beyond this project manager's knowledge.
- There is no methodology for directing the project team's thinking towards a solution. This is a major disadvantage of the trial-and-error method.

Figure 5.1 shows the randomness and weakness in searching for a solution using the "trial-and-error" method. A project manager needs to get from a known *problem* to a *solution,* whose location is not known, by using a certain concept "*C1*". When he realizes that concept "*C1*" is not a good solution to solve his contradiction, the project manager returns to his original problem by adopting a new concept "*C2*" and so on and so for. Usually, this cycle could be repeated for many trials before finding an adequate solution. This might not be correct for the experienced project manager but very true for the manager with limited knowledge who follows his Inertia Vector "*V*" that takes him in an opposite direction from the solution. It is very obvious that reaching a solution using this approach is time consuming and does not guarantee a solution.

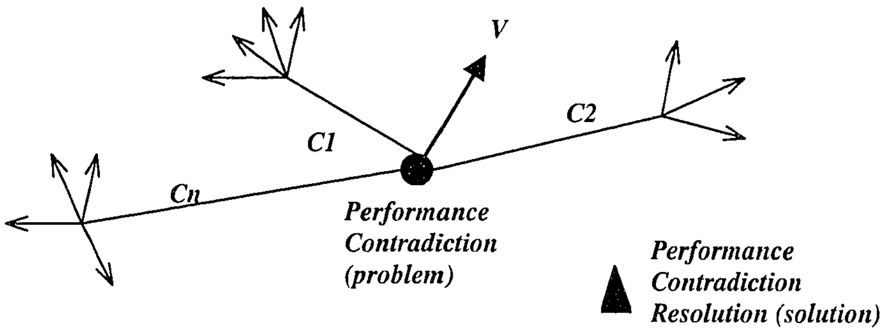


Figure 5. 1 Diagram showing a Trial-and-error search method

In 1953, the American psychologist, A. Osborn tried to overcome the drawbacks of the trial and error method. He assumed that some people could generate ideas easily but cannot analyze them, and vise versa. Osborn suggested separating the two processes. One group will generate ideas to solve the problem, and another group will only analyze the ideas (Altshuller 2000). The idea-generation team consists of people having different areas of expertise and any team member can express any idea without providing any proof. Although this technique, named by Osborn as "brain storming", improved the trial-and-error method, it did not eliminate the non-systematic search. It is currently used by many construction organizations where the project team members representing the various areas in a project (e.g. safety, quality, construction, procurement, etc.) meet and "brain storm" ideas and conflict resolution methods. The brainstorming process can produce positive effects when dealing with non-complex performance contradictions that involve two project objectives. However, it cannot lead to effective solutions in a timely manner when dealing with more complex contradictions that involve multiple project objectives.

Other tools are being used to improve the efficiency of problem solving and overcome the disadvantages of the trial-and-error and brain storming methods. For example, some construction organizations use various checklists, questionnaires, and decision aids. Very few companies use expert systems and knowledge databases to complement the project manager's knowledge. However, all these tools will provide limited help in problem solving but are not very effective because they provide information and information by itself does not generate solutions.

Based on above, there is a need to develop a performance conflict resolution methodology that helps the problem solver arrive at an acceptable and applicable solution in a timely manner. There are two major requirements for such a methodology:

1. It should have a *mechanism* for guiding the project manager to the most appropriate solution in a short time. This requirement solves the problem of the trial-and-error method.
2. It should lead the conflict solver to the most *promising* corrective action plan. It is very important to arrive at solutions that worked for identical situations and stood the test of time.

5.1.3 The Theory of Inventive Problem Solving (TRIZ)

This section will briefly introduce the Theory of Inventive Problem Solving (TRIZ), TRIZ tools, the 40 principles of TRIZ, the Technical Contradiction Matrix, and TRIZ applications in engineering and construction management.

5.1.3.1 Introduction to TRIZ

The Theory of Inventive Problem Solving (TRIZ) is a problem solving methodology that can help users solve simple and difficult problems efficiently and effectively. It is an algorithmic approach for solving difficult technical and technological problems. A Russian engineer and scientist, Genrich Altshuller, founded "TRIZ", an acronym in Russian for "Theory of Inventive Problem Solving", in 1946. Altshuller, after analyzing hundred thousands of patents, realized that there are objective laws, or trends, in the evolution of technical systems. His studies revealed that the evolution of engineering systems is not a random process, but obeys certain laws and that inventiveness and creativity can be taught. TRIZ theory states, "*The evolution of all technical systems is governed by objective laws*" (Altshuller 1998).

The TRIZ methodology has been widely taught in Russia, but it did not spread in North America until late 1980's. It is based on the following three assumptions or premises: (1) the ideal design with no harmful effects is a goal; (2) an inventive solution involves the elimination in whole or part of a contradiction; and (3) the inventive process can be structured.

TRIZ methodology is not a pure mathematical science but it is a combination of prescriptive and analytical tools that could help everyone in almost every domain to solve difficult problems efficiently and effectively. Due to its wide knowledge base, the TRIZ methodology allows its user to find solutions outside his professional domain. The theory focuses on solving contradictions in a system by avoiding compromises or tradeoffs. While reviewing thousands of worldwide patents, Altshuller investigated in particular the contradictions that were resolved *without compromise* (Altshuller 1998). It is now considered an international science of creativity and is being applied in various areas such as marketing, education, and psychology. For example, this study demonstrates that TRIZ approach could be used by construction managers to improve their problem solving capabilities of construction performance related problems. The TRIZ methodology is not intended to replace quality or process improvement systems used by companies, but it can be complimentary to such systems.

TRIZ research is based on the hypothesis that there are universal principles of invention that are the basis for creative innovations, and that if these principles could be identified, they could be taught to make the process of invention more predictable (Domb 2000). It should be emphasized that TRIZ is a new methodology, and its effective implementation requires a lot of training. The reader is referred to Savransky (2000) for a detailed introduction to TRIZ methodology.

5.1.3.2 General TRIZ Tools

The "General TRIZ Solutions" have been developed over the 50 years period of TRIZ research to make the solution of inventive problems a systematic process. These several basic TRIZ tools as well as other methods and techniques, developed by students and followers of Altshuller, make up what is known as systematic innovation. Some of these tools are prescriptive or qualitative such as:

- The 40 Principles of Inventive Problem Solving
- The separation principles
- The Technical Contradiction Matrix

The above tools are relatively simple and require the user to pre-formulate the contradiction in terms of standard parameters. They are basically used to solve non-complicated problems. More complicated problems are solved with some advanced and more analytical tools such as ARIZ.

- **ARIZ (Algorithm for Inventive Problem Solving)**

It is the central analytical tool of TRIZ and it provides sequential steps for solving complicated problems. ARIZ is a guide for thinking and should be followed step by step when solving complex problems. The latest version of ARIZ was published in 1985 and involves nine steps with each step containing many sub-steps (Altshuller 1998). For a detailed description of ARIZ see Altshuller (2000).

Other analytical tools include the following:

- The Ideal Final Result (IFR)
- Laws of Evolution of Technological Systems
- Functional Analysis
- Locating the Zones of Conflict (similar to Root Cause Analysis)
- Substance-field (Su-field) analysis
- 76 Standard Approaches to Inventive Problems based on Su-field analysis.
- S-Curve life line of technology
- Anticipatory Failure Determination (AFD)
- Directed Product Evolution (DPE)

For further information about TRIZ tools, the reader is referred to Fey and Rivin (1997). In order to develop a tool for Construction Performance Problem Solving, this research study will use two prescriptive TRIZ tools namely: (1) the 40 Principles of Inventive Problem Solving, and (2) the Technical Contradiction Matrix.

5.1.3.3 TRIZ 40 Principles of Inventive Problem Solving

Altshuller recognized that solutions to technical problems are derived from a similar set of laws and principles that are not associated with a particular field of engineering and these principles can be re-used to solve new problems. The 40 Principles of Problem Solving are a basic tool of TRIZ and are the principles that were found to repeat across many fields as solutions to a wide range of problems (Domb 2000). They are used to resolve technical contradictions that face the development of new products. The TRIZ research has identified 40 principles that solve these contradictions and are listed in Table 5.1. The reader is referred to Altshuller (1998) for further details on these principles.

Table 5. 1 TRIZ Principles for Inventive Problem Solving

No.	Principle	No.	Principle
1	Segmentation	21	Rushing Through
2	Extraction	22	Convert Harm into Benefit
3	Local Quality	23	Feedback
4	Asymmetry	24	Mediator
5	Consolidation	25	Self Service
6	Universality	26	Copying
7	Nesting	27	Dispose
8	Counterweight	28	Replacement of Mechanical System
9	Prior Counteraction	29	Pneumatic or Hydraulic
10	Prior Action	30	Flexible Shells and Thin Films
11	Cushion in Advance	31	Porous Materials
12	Equipotentiality	32	Changing the Color
13	Do It in Reverse	33	Homogeneity
14	Spheroidality	34	Discarding and Recycling
15	Dynamicity	35	Transformation Properties
16	Partial or Excessive Action	36	Phase Transition
17	Another Dimension	37	Thermal Expansion
18	Mechanical Vibration	38	Accelerated Oxidation
19	Periodic Action	39	Inert Atmosphere
20	Continuity of Useful Action	40	Composite Materials

5.1.3.4 Technical Contradiction Matrix

The TRIZ patent research classified 39 universal features (e.g. speed, stress, shape, etc.) for technical contradictions. Altshuller, after analyzing thousands of inventions, used these universal characteristics to develop the Contradiction Matrix. To display all the possible technical contradiction combinations, Altshuller developed a 39x39 matrix and identified which of the 40 inventive principles were applicable to the specific combination of contradiction parameters. This matrix is called the Technical Contradiction Matrix, an extract of which is shown in Table 5.2.

Table 5. 2 Extract from the TRIZ Contradiction Matrix

(The TRIZ Journal – July 1997). NOTE: The complete Contradiction Matrix is 39x39 cells and can be downloaded from *http://www.triz-journal.com*

Worsening Feature → Improving Feature ↓	**Weight of moving object**	**Weight of stationary object**	**Length of moving object**	**Length of stationary object**
	1	**2**	**3**	**4**
1. Weight of moving object	+	-	15, 8, 29,34	-
2. Weight of stationary object	-	+	-	10, 1, 29, 35
3. Length of moving object	8, 15, 29, 34	-	+	-
4. Length of stationary object		35, 28, 40, 29	-	+

To use the contradiction matrix, part of which is shown in Table 5.2, select the pair of features that best express the trade-off of conflict. For example, increasing the *length of moving object* will make the *weight of moving object* increase (i.e. deteriorate). The numbers in the intersecting cells (inside the oval) refer to the Principles of Invention (listed in Table 5.1) that are most likely, based on the TRIZ research, to solve the contradiction. In this case, Principles no. 8 (Counterweight), 15 (Dynamicity), 29 (Pneumatic or Hydraulic), & 34 (Discarding and Recycling) will most probably solve the problem. It should be emphasized that although the numbers in the cells of the matrix identify the principles leading to *highly probable* solutions, the solutions are not guaranteed.

5.1.3.5 TRIZ applications in Engineering and Project Management

TRIZ has been applied in many engineering and project management areas. Many global companies such as Ford, Procter & Gamble and Mitsubishi have implemented TRIZ to produce better products more efficiently (Rantanen and Domb 2002). Companies in areas as diverse as marketing, education and management are using TRIZ to solve their problems in a more effective and efficient manner. Domb (2000) demonstrated the effective use of TRIZ in enhancing the cost and schedule performance of new product development projects by managing technical risk. Stratton and Mann (2003) presented the common aspects and distinctions of TRIZ and the Theory of Constraints (TOC) in relation to the design of product and manufacturing systems. Kourmaev and Teplitsky (2003) applied TRIZ approach using examples from the pipeline technology. Stratton and Warburton (2003) applied TRIZ to supply chain management and demonstrated how TRIZ separation principles and the Theory of Constraints (TOC) can be integrated for a more efficient supply chain. Chang and Chen (2004) presented conflict resolution CAD software, Eco-Design Tool, which integrated TRIZ into the eco-innovation idea and provided balance between technical innovation and environmental protection.

Royzen (1993) discussed the benefits of applying TRIZ in value management and quality improvement. The study demonstrated how TRIZ and engineering creativity could increase work effectiveness. Dull (1999) discussed the integration of Value Engineering (VE) with TRIZ to maximize work effectiveness and enhance problem solving. The study listed the strengths and weaknesses of VE and TRIZ and proposed integrating the two methodologies to obtain more comprehensive results. The author concluded that VE/TRIZ integration is most applicable in complex technical projects where resource expenditure can be sustained.

Mohamed (2002) presented the first research effort in the field of construction engineering and management. He demonstrated the use of TRIZ as a decision-making tool in the construction industry. Using a number of case studies in utility tunnel construction, the author highlighted the advantages and limitations of TRIZ. Also, the study used TRIZ concepts to develop a new approach for extracting and consolidating the technical knowledge used to solve construction field problems. Moreover, the research presented a simulation framework based on TRIZ concepts that is expected to enhance the capabilities of the current construction simulation techniques through systematic improvement of construction techniques.

A comprehensive literature review on the applications of TRIZ in the domain of project management and controls did not reveal any. This study represents the first research effort in the implementation of TRIZ to solve construction performance and control problems. This initial attempt is expected to trigger many researches on the application of TRIZ in construction project management.

5.1.4 The Techniques for Resolving Performance Contradictions (TRAC)

This section presents the TRAC methodology for solving performance contradictions among the competing performance indices. It covers the following: (1) TRAC definition, (2) TRAC methodology, (3) TRAC components (4) the 40 Principles for Resolving Performance Contradictions, (5) the Performance Contradiction Matrix, (6) the TRAC process, (7) TRAC features, and (8) demonstrating the use of the Contradiction Matrix.

5.1.4.1 Definition of TRAC

In today's competitive construction industry, there is less and less time to react to project performance challenges in a dynamic and changing environment. Project managers need to act adequately and within a short time to correct any slippages and get back on target. Consequently the ability to identify and resolve performance problems is extremely important for project managers. The Techniques for Resolving Performance Contradictions (TRAC) is a problem solving methodology that increases as well as accelerates the project team's ability to solve conflicts and contradictions between the project's competing objectives. TRAC, whose objective is to solve project performance contradictions, uses TRIZ Principles and the idea of the Contradiction Matrix. Table 5.3 shows a comparison between TRIZ and TRAC. The fact that TRIZ uses a limited number of principles (40) to solve technical contradictions provides an opportunity to use the same principles to solve non-technical problems and namely performance problems. In almost every project, the performance variables of cost, schedule, safety, quality, and customer satisfaction put limits on management in terms of viable corrective action plans, and forces, in most cases, a degree of compromise. The TRAC concept introduced in this study emerges to acknowledge performance conflicts and the need to minimize conflict between competitive project goals such as schedule and safety or cost, profitability, and quality. The concept behinds TRAC is that identifying and minimizing conflict among competing performance indices can be structured.

Table 5. 3 Comparison between TRIZ and TRAC

TRIZ	***TRAC***
- *Solves Technical Contradictions*	- *Solves Construction Performance Contradictions*
- *40 Principles for Inventive Problem Solving*	- *40 Principles for Resolving Performance Contradictions*
- *39 universal technical characteristics (e.g. speed, stress, shape, etc.)*	- *8 standard project performance attributes or indices (e.g. cost, schedule, quality, safety, etc.)*
- *Technical Contradiction Matrix*	- *Performance Contradiction Matrix*

5.1.4.2 TRAC methodology

The TRAC methodology is based on the following three assumptions: (1) a workable and viable corrective action plan that is achieved through minimal conflict among the competing performance indices is the goal; (2) a good corrective action plan involves the elimination in whole or part of a performance contradiction; and (3) the performance conflict resolution process can be structured. It should be emphasized that some companies in the past have solved the majority of construction performance contradictions. The issue resides in problem definition and in the lack of a structured methodology, using accumulated knowledge, to solve contradictions. To address the issue, this study is proposing a generic system, TRAC, to assist the construction sector identify performance problems in an efficient and effective manner. TRAC can be defined as a *user-oriented, knowledge-based, systematic, and adaptable* methodology for resolving construction performance contradictions.

User-oriented: The TRAC algorithm is developed to guide users like project managers and it is not a program to be used by a machine or computer. The algorithm is based on studying the useful and harmful interactions among the various project performance indices and the application of project and construction management/control techniques to minimize the harmful effects and maximize the useful interactions. The objective of TRAC is to guide the user in his search for a solution and does not generate or guarantee a ready and workable solution. This guidance expedites the search and allows the decision maker to focus on the most promising and effective corrective action plans. The knowledge, experience, and judgment of the user (e.g. project manager) are needed to supplement the proposed framework and consequently the human element is vital for proper implementation of TRAC.

Knowledge-based: The knowledge about the generic conflict resolution heuristics should be compiled from case studies/lessons learned and the body of knowledge of project management. The proposed principles to minimize or completely remove contradictions among the project performance attributes are listed in section 5.1.4.4.

Systematic: Procedures for solving performance contradictions are designed and presented in a structured manner. TRAC is an algorithm made up of a regulated sequence of steps that are necessary for solving the contradiction. The process is basically composed of four steps: (1) specifying the performance contradiction; (2) generalizing the performance contradiction; (3) generalizing the solution to the performance contradiction; and (4) proposing specific solution in the form of specific corrective actions to minimize the specific performance conflict.

Adaptable: TRAC is adaptable because the same performance contradiction can be solved with more than one approach depending on the project manager solving the problem. Different users can produce different solutions to the same problem. TRAC does not ignore the project manager's knowledge, experience, and his lessons learned from past projects. On the contrary, TRAC utilizes the user's experience, creativity, and his personal approach for problem solving. TRAC provides the methodology that leads project managers toward an effective solution for their problem and does not recommend or impose a specific solution. The algorithm *does not* replace the project manager but can accelerate the conflict resolution process. Moreover, TRAC library of principles is generic and can be customized to include more principles or conflict resolution concepts that are specific to the implementing construction organization.

5.1.4.3 TRAC components

The Techniques for Resolving Performance Contradictions (TRAC) consist mainly of two components as shown in Figure 5.2: (1) The 40 Principles for Resolving Performance Contradictions (PRPC), and (2) The Performance Contradiction Matrix (PCM). The next section will explain the two components.

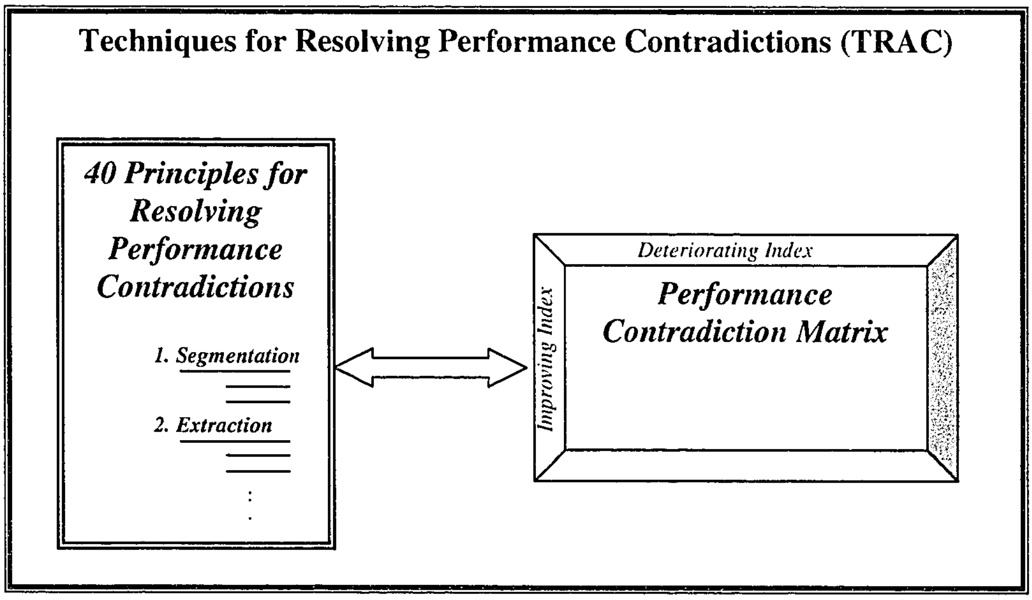


Figure 5. 2 Components of TRAC

As with any decision support tool, TRAC can only lead to satisfactory results if the user's knowledge of the tool is satisfactory. Also, the user must have good project/construction management knowledge.

5.1.4.4 The 40 Principles for Resolving Performance Contradictions

The forty Inventive Principles discovered by Genrich Altshuller have found applications in many non-technical areas like business (Mann and Domb 1999), quality management (Retseptor 2003), education (Marsh et al. 2004), social applications (Terninko 2001), and architecture (Mann and Cathain 2001). This was feasible because these principles are fundamental and universal. The potential of applying TRIZ techniques in the domain of project management is very high. The objective of this section is to apply, in an analogous way, the 40 inventive principles of TRIZ in the context of construction performance management environment. After having identified above the importance of completely eliminating or minimizing conflict among the eight project performance indices, this study will attempt to demonstrate that TRIZ principles, although applied in purely engineering and scientific context, are also applicable in a construction project management context. This section provides numerous examples related to construction performance that demonstrates how extensively these 40 inventive principles could be used in the area of project management. The following is a list of the 40 Principles as applied to construction performance management.

Principle 1. Segmentation

A. Divide an object into independent parts.

Construction performance analogy:

- Divide the Project by phase, area, and system.
- Divide the Overall project goal into many goals.
- Divide the project by areas of responsibility via an Organizational Breakdown Structure (OBS).
- Divide a large project into smaller sub-projects.

- Use project segmentation where by the work content is divided into several sub-projects or segments so that the same set of activities is performed on each segment. Executing work in parallel can reduce the project duration.
- Divide each sub-project into different cost centers.
- Divide a contract into smaller sub-contracts.
- Divide a Purchase Order (quantity wise) into smaller orders.
- Divide a Purchase Order (time wise) into smaller orders.

B. Make an object sectional (for easy assembly or disassembly).

- Project construction management team
- Empowerment or the segmentation of the decision making process.
- Use modular site offices.
- Use modularization in design
- Concurrent engineering team
- Safety and quality project committees.

C. Increase the degree of an object's segmentation.

- Apply method statements to provide a step-by-step procedure to carry out critical construction tasks.

- Develop detailed procurement and construction schedules using PERT, CPM, Gantt, and Line of the Balance Method.
- Develop manpower histograms, cash flows, and detailed budgets.
- Divide each project goal into its sub-goals. For example dividing the project cost goal into indirect, material, labor, and equipment cost sub-goals.
- Divide the work into manageable units using a Work Break Structure (WBS) and/or a Cost Breakdown Structure (CBS).
- Divide a complex activity into sub-activities.
- Develop Decision Trees and Pareto diagrams.
- Utilize modularization as much as possible.

Principle 2. Extraction (Extracting, Retrieving, Removing)

A. Extract the "disturbing" part or property from an object.

- Outsourcing Manpower.
- Identify and extract the critical items from scope of work in order to remove the "*disturbance*" or criticality.
- Avoid competitive tendering cycle by sole sourcing (vendors, sub-contractors).
- Avoid risks by sub-contracting specialty works.
- Using external laboratory testing.

- Elimination of non-value added activities through value engineering and management. Value management is structured approach and effective methodology for achieving “best value-for-money” in any construction project.

- Removal of unskilled staff and labor at the initial phase of work (through evaluation and assessment).

- Make quality and safety audits independent of project management. Auditors will report to executive management.

B. Extract the necessary part or property from an object.

- Separate critical issues and major cost/schedule variances for better analysis.

- Use management by exception.

Principle 3. Local quality

A. Transition from homogeneous to heterogeneous structure of an object

- Prioritize project goals and assign different weights based on significance.

- Assign different levels of risks to project activities (e.g. high, medium, low).

B. Make each part of an object function in conditions most suitable for its operations.

- Employ project personnel that are specialized in their own fields and capable of carrying out their functions in an efficient and effective manner.

- Hire different specialists for different functions.

- Do not overload a single member of the team with many functions.

C. Each part of an object should be placed under conditions that are most favorable for its operation.

- Use the right personnel, tools, and equipment for the right task at the right timing.
- Match personality types to the assigned tasks when forming a project team.

Principle 4. Asymmetry

A. Replace symmetrical form(s) with asymmetrical form(s).

- Employ a workforce which is heterogeneous and made up of different skills.

B. If an object is already asymmetrical, increase its degree of asymmetry.

- Adapt systems to meet specific project requirement.
- Site Planning and mobilization plan for each individual project.

Principle 5. Consolidation

A. Consolidate in space homogeneous objects, or objects destined for contiguous operations.

- Place functional groups together for better communication and coordination (e.g. engineering staff to work in one place). Scattering homogenous teams reduce efficiency.
- Let team members who get well with each other work closely.

- Breakdown communication barriers between the project disciplines by placing all project staff in one office complex.
- Implement team approach to solve problems.
- Enhance brainstorming, and group decision-making.
- Conduct team meetings and bring collective judgment to handle project problems.

B. Consolidate in time homogeneous or contiguous operations.

- Carry out similar construction activities within the same time framework. For example, constructing underground utilities (sewer, gas, power, water etc.) at the same time will minimize underground disruption.
- Schedule parallel activities (e.g. engineering and procurement) to reduce the project duration.
- Use of "concurrent engineering" or the simultaneous progress of activities to expedite the project.
- Offsite "Prefabrication" to advance the construction.
- Use of "fast-track" construction in "Design and Build" projects.
- "Partnering" in construction projects could reduce cost, duration, conflict, litigation and claims.

Principle 6. Universality

A. An object can perform several different functions; therefore, other elements can be removed.

- Apply integrated project management systems to control construction projects (e.g. ERP systems). Other standalone programs can be removed.

- Hire multi-skilled personnel for critical tasks.

- Enhance cross-functional training within the construction project organization. For example, Safety officer acts as quality coordinator, and team leader acts as timekeeper in addition to his duties.

- Use multi-functional construction equipment (e.g. equipment that can work as excavator and dumper) and tools. For example, the addition of heat nozzles to a rotor excavator working in frozen ground can increase its productivity.

- Make project standards universal. This is possible by standardizing project procedures, specifications, construction methods, material procurement processes, inspection and testing procedures, progress measurement, etc.

- Create computerized templates and generic checklists for quality, safety, cost control, site progress, labor and equipment time sheets, etc.

Principle 7. Nesting

A. One object is placed inside another. That object is placed inside a third one, etc.

- Project organization structure – several people within each organizational unit.

- Hierarchy of client expectations.

- Introduce voids into 3D shapes (e.g. dry walls).

B. An object passes through a cavity in another object.

- Allow any member within the project staff or project organizational unit to communicate directly with the project manager or company management.
- Expose project staff to external parties (e.g. client feedback, environmental agencies and regulations)

Principle 8. Counterweight

A. Compensate for the weight of an object by combining it with another object that provides a lifting force.

- Build alliances and partnerships with vendors, fabricators and sub-contractors.
- Assign project sponsors.
- Project manager to obtain senior management on-going support.
- Obtain management and staff support (e.g. through presentations) before implementing new systems (e.g. quality or cost control systems).
- Use of cranes in construction to install heavy equipment and construction modules.
- Apply revenue front-loading (through unbalanced bids) to enhance cash flow and project profitability.

B. Compensate for the weight of an object with aerodynamic or hydrodynamic forces influenced by the outside environment.

- Compensate for the complex organizational structure of a company with a less hierarchical project organization and other ad-hoc committees.
- Use automation in construction and technology to make some risky activities safer to perform and be executed in less time.

Principle 9. Prior Counteraction

A. If it will be necessary to perform an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.

- Implement customer satisfaction surveys.
- Implement project team satisfaction surveys.
- Implement a proactive (rather than reactive) approach across the project.
- Propose corrective action and preventive measures.
- Use forecasting techniques using Earned Value Analysis, mathematical models (e.g. Markov), simulation analysis, neural networks, Fuzzy logic, etc.
- Use project management techniques (e.g. PERT, Resource Planning, earned value analysis).
- Apply formal Risk Management methods to minimize or mitigate risks. A successful contractor must know how to manage the project risks.
- Carry out constructability studies prior to start of construction.

- Use capital budgeting techniques to selection optimal alternatives.

B. Create beforehand actions in an object that will oppose known undesirable working stresses later on.

- Correction of non-conformances at an early stage of the project.
- Pre-qualification of vendors and sub-contractors.
- Early order of long lead items.
- Verification and validation of construction methods (e.g. using simulation).
- Use of prototypes and construction mock-ups.
- Maintain accurate log of actual schedule and cost data for possible use in future claims.
- Heavy lift reviews and planning.
- Use of pre-stressed concrete.
- Geo-technical and material testing (e.g. testing concrete compressive strength and soil compaction).
- Screening and testing applicants.
- Conducting quality and safety audits.
- Conducting trend analysis during the early phase of the project to forecast slippages in order to take corrective action.
- Utilize project management by early warnings. This tool is based on the assumption that early warnings

observed in project activities could help project managers to better manage or forecast project problems.

- Engage project staff and labor in open discussions to avoid future misunderstanding. Before implementing a change, get the affected people involved so they can participate in the planning and implementation of changes and don't feel threatened.

Principle 9 (inverted). Post Counteraction

- Post-project evaluations and reviews.
- Lessons learned.

Principle 10. Preliminary action

A. Perform, before it is needed, the required change of an object (either fully or partially).

- Construction Pre-planning and setting up project controls philosophy and procedures.
- Feasibility studies, forms, and procedures.
- Staffing and manpower planning.
- Off-site fabrication.
- Training, team building and orientation of project team.
- Prepare lessons learned for future projects.

B. Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.

- Pre-fabrication of modules.
- Use Pre-cast concrete.
- Flowcharts for construction and procurement processes.
- Arrange site offices, warehouses, fabrication shops and all temporary facilities and utilities.
- Pre-assembly of construction components (can save time during site construction).
- Pre-order standard construction material.

Principle 11. Cushion in Advance

A. Compensate for the relatively low reliability of an object with emergency measures prepared in advance.

- Emergency construction site evacuation plan.
- Alternate vendors and suppliers (e.g. second source of concrete supply).
- Back-up generators for site office and for night construction.
- Back-up computer data.
- Project contingency planning and risk management.
- Emergency stairways/fire-escapes for site office, first aid and rescue kits.

- Built safety factors (e.g. scaffolding systems, rigging operations).
- Excess inventory for critical material/tools.

Principle 12. Equipotentiality

A. Change operating conditions to eliminate the need to work against a potential field (e.g. eliminate the need to raise or lower objects in a gravity field).

- Flat project organization with fewer hierarchical steps. Bring team members to the same level.
- Homogeneous project teams with identical skills and operating at the same wavelength.
- Resource leveling of construction manpower. Minimizing peaks and valleys in the construction histogram will enhance labor productivity and schedule performance.
- Nominal group technique to bridge the gap between project staff of different skills. It balances participation across team members and minimizes the influence of the construction team leaders.
- Construct site facilities and utilities at the same level.
- Ramps for warehouse.

Principle 13. Do It in Reverse

A. Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).

- *Training* the project and construction labor force instead of *using* them will contribute to the success of project.
- Blame the process not the individual.
- Encourage the project owner to complain in a positive and proactive manner. The client feedback will enhance project management performance.
- Work at home during weekends instead of wasting time through travel.
- Find your solution to a problem in a consultant's database (e.g. Primavera) instead of having the consultant find a solution to your problem.

B. Make movable parts (or the external environment) fixed, and fixed parts movable.

- Moving conveyor belts to transport material from warehouse to site.
- Instead of construction labor having to come to an offsite place to eat or get medical attention use traveling medical and food facilities. For example, have water delivered to the labor as this minimizes idle time.
- Instead of dissatisfied clients coming to you, go to them and listen to their concerns.
- Apply Management By Walking Around approach.

C. Turn an object (or process) 'upside down'.

- Upward vs. downward flow of communication.
- Have project employees assess themselves.

Principle 14. Spheroidality - Curvature

A. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.

- Use rounded construction elements like arches and domes for strength.
- Use 3D computer models to simulate critical construction processes rather than 2D equations or drawings.
- Rounded personalities for project team leaders can provide better customer service and can better handle project problems.
- Rotate team leadership.
- Circulate information and progress reports among team members rather than using linear hierarchical flow of information.
- Apply shortcuts and deviation requests to circumvent the established rules.
- Smoothing technique for conflict resolution to emphasize areas of agreement and break the rough points of disagreement.
- Circular-section buildings and warehouses: maximum space coverage with minimum material consumption.
- Curved floor edges make room floors more easy to clean

- Rounded edges will enhance appearance of many architectural items.
- Use curved retaining walls provide better strength.

B. Use rollers, balls, and spirals.

- Implement Quality circles.

C. Go from linear to rotary motion, utilize centrifugal force.

- Use of Revolving doors help conserve heat transfer in construction offices.
- Rotating construction equipment instead of fixed ones.
- Casting of concrete structures in a centrifugal manner.
- Encourage "out of the box" thinking rather than linear thinking.

Principle 15. Dynamics

A. Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.

- Procedures to handle changes in scope of work.
- Flexible construction office layouts with movable partitions.
- Ad-hoc committees to handle dynamic construction situations.
- Timely and periodic update of project performance data such as schedule, cost, safety and quality.

- Dynamic update of at-completion construction cost and duration.

B. Divide an object into parts capable of movement relative to each other.

- Apply control and movement joints.

C. If an object (or process) is rigid or inflexible, make it movable or adaptive.

- Construct retractable roof structures.
- Apply flexible joints
- Use Floating floors
- Construct Multi-purpose halls
- Use escalators and elevators instead of stairs.
- Use moving targets.
- Adopt flexible project organizational structure. Rigid structures can't handle changes effectively.
- Employ flexible project staff (e.g. using temporary workers, overtime, double shifts, and multi-functional personnel).

Principle 15 (inverted). Static

- Minimize variation or freeze scope of work.

Principle 16. Partial or Excessive Action

A. If 100% of a solution is hard to achieve, then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.

- Dip a brush in paint to get excess paint, and then let the excess drip off.
- Over-fill holes with plaster and then remove excess and smoothen surface.
- Apply safety margins. Over designing (minimal) of structural members will provide a safety factor.
- Slightly under design (say 95%) is often the practical solution for some systems (e.g. heating systems, transportation systems, parking, etc.)
- Handle the most critical items and assign priorities when not all items and issues can be acted upon with the available resources.
- Use stretch project goals and objectives (e.g. a Schedule performance index of 1.1 instead of 1.0).
- Exceed client's expectations.
- Permitted tolerance in construction progress measurement.
- Compromise at conflict resolution.
- Compromise or flexibility in the application of change management procedures (e.g. construction of "out of scope" item prior to client approval due to a client request or to expedite schedule).

Principle 16 (inverted). Complete Action

- "Zero harm" construction safety.
- "100% schedule" project delivery.

Principle 17. Another dimension

A. Move an object or system in two- or three-dimensional space.

- Use of 3D trusses and structures.
- Use a multi-level arrangement to store construction materials rather than a single-level arrangement.
- Matrix project organizational structure vs. one dimensional or functional structure.
- Multi-disciplinary and cross-functional project teams.
- Multi-dimensional project goal structure covering multi-project attributes and success criteria.

B. If an object contains or moves in a plane, consider use of dimensions or movement outside the current plane.

- Use corrugated roofing materials with high stiffness and low weight
- Insert irregularities into a wall before plastering to improve adhesion of plaster.
- Curved or profiled roofing materials can withstand longer spans.

C. Use a multi-storey arrangement of objects instead of a single-storey arrangement.

- Multi-storey site offices

D. Tilt or re-orient the object, lay it on its side.

- Horizontal flow of communication within project management.

E. Use 'another side' of a given area.

- Assess the quality of constructed work by external inspectors.
- Audit quality and project procedures using external auditors.
- Conduct peer reviews and cold-eye reviews on drawings, construction method, cost control procedures, etc.

Principle 18. Mechanical vibration

A. Cause an object to oscillate or vibrate.

- Use of vibrators removes voids from poured concrete
- Frequent or periodic communication and cooperation in many directions.
- Engineering and construction coordination in projects is an analog of mechanical vibration.
- Vibration can be used as a metaphor for exciting the project team to obtain coordinated action. Excitement or vibration can be achieved though rewards, motivational speeches, bonus, etc.

B. Increase its frequency (even up to the ultrasonic).

- Use of ultra-sound for non-destructive crack detection.

C. Use an object's resonant frequency.

- Use of resonance to speed up the flow of concrete from hopper.

D. Use piezoelectric vibrators instead of mechanical ones.

- Use motivational techniques to maintain good project staff performance and good labor productivity.

E. Use combined ultrasonic and electromagnetic field oscillations. (Use external elements to create oscillation/vibration).

- Use of geo-physics techniques to identify the sub-soil formation.
- Top management to periodically motivate the project team and increase their morale.
- Employ a third party to assess the project team performance.
- Bring new staff with new skills into the team.
- Project management to keep the team challenged.

Principle 19. Periodic action

A. Instead of continuous action, use periodic or pulsating actions.

- Periodic project performance reviews.
- Periodic progress status reports.
- Periodic quality audits.
- Periodic showers use less water than conventional continuous showers.
- Use bollards or poles instead of continuous walls.

B. If an action is already periodic, change the periodic magnitude or frequency.

- Measure performance and progress on a weekly basis instead of monthly.
- Change the frequency of quality audits.

C. Use pauses between actions to perform a different action.

- Perform preventive maintenance of construction equipment during idle time like lunch breaks or non-working days.
- Conduct staff training during lunch hours or on weekends.
- Staff and labor to take some rest or breaks between work shifts.
- Use total float in construction activities to level the project manpower histogram.

Principle 20. Continuity of useful action

A. Carry on work continuously; make all parts of an object work at full load or optimum efficiency, all the time.

- Continuous improvement in safety and quality performance.
- Continuous training and upgrade of staff.
- Continuous improvement of construction process and techniques.
- Continuous measurement of labor productivity.

- Continuous implementation and follow-up of corrective action plans.
- Continuous work by crews on activities without interruptions will enhance efficiency through the learning curve effect. Mobilization/demobilization of work force will lead to low productivity.

B. Eliminate all idle or intermittent actions or work.

- Variance analysis and corrective action to minimize slippages and enhance productivity.
- Resources leveling to minimize idle time of resources like labor and equipment.
- Reduce or eliminate staff turnover.
- Reduce circulation or idle space in offices.

Principle 21. Rushing Through

A. Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.

- Continuous pouring of concrete at high rate.
- Carryout major critical process (e.g. reengineering, project re-organization) in a short period and with full participation of all parties at the same time.
- Promptly replace incompetent project staff.
- Quickly implement critical (unpleasant) corrective measures.
- Quickly introduce major cost-saving techniques.

- Quickly resolve conflicts among project participants.
- Quickly remove wrong instructions, invalid or obsolete procedures.

Principle 22. Convert Harm into Benefit

A. Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.

- Use wasted energy to generate electric power.
- Use negative criticism from the project owner or complaints from project staff to make positive changes.
- Use top management complaints as opportunities for project performance improvement.

B. Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.

- Eliminate project team fear of using new processes and techniques by introducing fear of loosing a competitive edge in the construction market.

C. Amplify a harmful factor to such a degree that it is no longer harmful.

- Reduce number of project staff as well as direct labor to a level where new innovative methods (e.g. automation, robots) have to be utilized.

Principle 23. Feedback

A. Introduce feedback (referring back, cross-checking) to improve a process or action.

- Project performance measurement and variance analysis.
- Management reviews.
- Client satisfaction surveys
- Project team satisfaction surveys.
- Quality and safety audits and reviews.
- Obtain feedback from vendors and sub-contractors.
- Obtain feedback from experienced construction supervisors.

B. If feedback is already used, change its magnitude or influence in accordance with operating conditions.

- Obtain feedback more frequently.
- Involve manufacturers, fabricators, and sub-contractors in value engineering and constructability reviews during early construction planning stage.
- Increase frequency of inspection for critical construction operations.

Principle 23 (inverted). Feed forward

- Forecast of cost and schedule at completion.
- Trend analysis and predicting project performance at completion.

Principle 24. 'Intermediary'

A. Use an intermediary carrier article or intermediary process.

- Independent laboratory testing.
- Top management involvement to monitor the project safety and quality performance.
- Use facilitators at brainstorming and team building sessions.
- Sub-contract non-critical activities (e.g. labor transportation, site cleaning) or highly specialized work (e.g. control systems, modeling).

B. Merge one object temporarily with another (which can be easily removed).

- Use arbitrators for critical and difficult negotiations.
- Hire temporary project employees or specialists for short-term assignments.
- Hire consultants for short periods (e.g. value engineering, risk analysis and value engineering consultants).

Principle 25. Self-service

A. Make an object serve or organize itself by performing auxiliary helpful functions

- Self-assessment
- Self-inspection.
- Self-improvement.
- Use of Self-leveling screed.

B. Use waste resources, energy, or substances.

- Utilize heat from a process to generate electricity.
- Solar panels/collectors to generate heat or electrical power.
- Use waste concrete for small miscellaneous work (e.g. concrete spacers, curbs, etc).
- Brick rubble used for hardcore.
- Use scrapped construction material for experiments.
- Re-hire retired project staff for projects that require their experience.

Principle 26. Copying

A. Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.

- Use simulation and Virtual reality to model construction operations.
- Use mock-ups in construction.
- Use architectural presentation boards to coordinate floor-wall-roof finishes.
- Study identical projects to identify improvement opportunities and lessons learned.
- Use performance-forecasting models to predict project at-completion performance.

B. Replace an object, or process with optical copies.

- Carryout surveying from aerial photographs instead of ground surveys.
- Use computer scheduling and cost control programs instead of manual methods.
- Use of electronic databases instead of paper records.
- Use of video-conferencing instead of travel.
- Use of computer simulation instead of physical models.
- Use of virtual prototypes instead of physical ones.

C. If visible optical copies are already used, move to infrared or ultraviolet copies.

- Use simulation and case studies instead of lecture style training.
- Use UV as a crack detection method.
- Use of ground penetrating radar (GPR) to detect underground utilities instead of conventional methods.
- Use of nuclear gages for soil density measurement instead of classical method.
- Use of X-rays to detect structural defects.

Principle 27. Cheap short-living objects

A. Replace an expensive object with a multiple of inexpensive objects, compromising certain qualities (such as service life, for instance).

- Sub-contract specialty work.
- Hire temporary project staff for non-critical activities.
- Use inexpensive tools, equipment, and material for non-critical processes.

Principle 28 Replacement of Mechanical System

A. Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.

- Replace manual or mechanical construction tools with optical tools.
- Use smart building management systems.
- Use of Light-locks
- Wireless data transmission between computer systems.

B. Use electric, magnetic and electromagnetic fields to interact with the object.

- Electric lock 'keys'.
- Electric fences.
- Electronic bar coding and electronic sensors for material management.
- Electronic tagging.
- Electronic communication (e.g. e-mails).
- Electronic data processing and transmission.

C. Change from static to movable fields, from unstructured fields to those having structure.

D. Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.

Principle 29. Pneumatics and hydraulics

A. Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).

- Flexible (fluid) project organization structure vs. a rigid one.
- Hydraulic elevator systems replace mechanical ones.
- Use of Self-leveling screed.
- Use water level to ensure flat surface for foundations
- Warm air heating systems

Principle 30. Flexible shells and thin films

A. Use flexible shells and thin films instead of three-dimensional structures

- Flat project organizations have the advantage of better and fast communication between the project manager and the labor force.

B. Isolate the object from the external environment using flexible shells and thin films.

- Protect company proprietary knowledge from general knowledge.

Principle 31. Porous materials

A. Make an object porous or add porous elements (inserts, coatings, etc.).

- Cavity wall insulation
- Set-up and maintain a project website.
- Set-up information sessions and tool box meetings for staff and labor.
- Make the project organization "porous" by having smooth flow of information across the system. Also top management as well as the client can easily penetrate the organization to obtain the information they need.

B. If an object is already porous, use the pores to introduce a useful substance or function.

- Desiccant/pest repellent in cavity wall insulation
- Improve project communications by establishing a project intranet that is accessible to all participants at all levels.
- Introduce new ideas and concepts to project staff.

Principle 32. Changing the Color

A. Change the color of an object or its external environment.

- Enhance cultural diversity within the project team.
- Develop community and business partnerships.

B. Change the transparency of an object or its external environment.

- Clear project vision and mission statement.

- Clear project objectives and scale of performance measurement.

- Modify (decrease) the transparency of the project information by having a computer firewall. The wall is transparent for project users and impermeable for outsiders seeking critical information.

C. In order to improve observation of things that are difficult to see, use colored additives or luminescent elements

- Post critical project information on walls using colored fonts to attract the attention of the project team (e.g. project mission, project milestone dates, project organization, flowcharts, etc.)

D. If such color additives are already used, employ luminescent traces or trace atoms.

Principle 33. Homogeneity

A. Make objects interacting with a given object of the same material (or material with identical properties).

- To avoid cracking make sure that interacting materials have similar coefficients of expansion

- Hire local labor to better understand the cultural background of local clients.

- Hire local fabricators to better control the fabrication schedule.

- Use common data transfer protocols among different computer platforms.

Principle 34. Discarding and recovering

A. Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.

- Reuse form-work for concrete
- Downsize project staff and labor force as the project moves into completion.
- Dissolve the project organization at the end of the project closeout period.
- Hire and fire temporary team members for short-term activities.
- Employ contract labor when needed and demobilize when their job is done.

B. Conversely, restore consumable parts of an object directly in operation.

- Apply warranty for all major constructed project systems and facilities.
- Carry out re-training for project staff.

Principle 35. Transformation of Properties

A. Change an object's physical state.

- Pouring concrete.
- Use virtual prototyping and computer simulation instead of physical simulation.
- Convert paper systems into computerized system.
- Convert manual construction methods to semi-automated methods.

B. Change the concentration or consistency.

- Change aggregate mix in concrete or asphalt.
- Dilute paint.
- Change the team structure.

C. Change the degree of flexibility.

- Flexible and variable-sized project teams.
- Increased flexibility of employee benefit programs.
- Flexibility in working hours.
- Different approach for each project participant (e.g. vendor, owner, subcontractor).

D. Change the temperature.

- Get project employees excited about their future with the construction organization after the project is done (by providing insight into future projects, and the company strategic plan, etc.).
- Provide full time employees with stock options, personal development, and involvement in planning.
- Get the owner excited about the project by presenting the benefits and advantages of the final product.

Principle 36. Phase transition

A. Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).

- Be aware of the construction project phases: Procurement, Construction, and, Commissioning/start-up.

- Be aware of the procurement stages: Request for Quotation, Tendering, Tender evaluation and approval, Placing Purchase Order, Fabrication, and delivery to site.

- Be aware of the Project Controls Stages: Establishing baselines, Progressing, Variance analysis, Corrective action and follow-up.

- Be aware of the Team Development Phases: Forming, Building, and Performing.

- Use periods of structural changes in a project (e.g. major internal organizational changes) in a positive way to introduce new processes and get rid of obsolete practices.

Principle 37. Thermal expansion

A. Use thermal expansion (or contraction) of materials.

- Expand approved scope of work.

- Expand marketing the contracting company.

- Empower the project team members (expansion of power).

- Use expansion joints

B. If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.

Principle 38. Accelerated Oxidation

A. Replace common air with oxygen-enriched air.

- Replace classical construction material (e.g. metal rebar) with innovative ones (e.g. fiber rebar).
- Replace classical construction equipment with more efficient and automated ones (e.g. Robots and laser operated machines).
- Replace classical construction material with innovative ones.
- Replace independent or stand alone project management systems with integrated systems (e.g. Enterprise Resource Planning (ERP) systems).
- Replace "meet the client expectation" mission with "exceed the client expectations".
- Replace non-motivated project employees with high performers.
- Replace old and classical employees with young, energetic, and highly creative individuals.

B. Replace enriched air with pure oxygen.

C. Expose air or oxygen to ionizing radiation.

D. Use ionized oxygen.

E. Replace ionized oxygen with ozone.

Principle 39. Inert atmosphere

A. Replace a normal environment with an inert one.

- Assign 'Quiet' and "No Smoke" areas in the project office buildings.

- Maintain a working environment that is free of negative criticism, complaints, and office politics.
- Encourage multi-cultural acceptance.
- Use the Nominal Group Technique.
- Install fire extinguishing systems

B. Add neutral parts, or inert additives to an object.

- Use neutral third parties during critical negotiations.
- Invite outside experts into project sessions like value engineering, risk analysis, and constructability.
- Use breaks in long project meetings for rest and reflection.
- Add Non-flammable material into cavity walls.
- Use Dampers and Sound Absorbing Panels.

Principle 40. Composite materials

A. Change from uniform to composite (multiple) materials.

- Form multi-disciplinary and cross-functional project teams that are usually more effective than teams having expertise in one field.
- Use of multi-media presentation in training is more effective than single media ones.
- Mix of theoretical and practical thinking skills within the team.

- Mix of senior and junior staff.
- Mix of skilled and semi-skilled labor crews.
- Mix of local and expatriate labor.
- Combine multiple communication methods for effective flow of project information (e.g. news letter, progress meetings, project Intranet, etc.).
- Apply composite training methods using lectures, hands-on learning, simulation, etc.
- Hire full time and contract employees.
- Form project teams of different personality types.
- High risk / low risk construction schedules.
- Use composite construction material like rebar reinforced concrete, glass reinforced plastic, and fiber reinforced concrete.

TRAC principles for performance conflict resolution may direct the project manager to solutions or corrective action plans that may exist outside the construction industry. The multi-disciplinary nature of TRAC principles increases the boundaries of the solution space. Some of the principles include ideas that may seem to be out of context but if properly investigated could lead to highly effective solutions. In TRIZ, seeking solutions only in one's own field of expertise is called "psychological inertia" because it is easy for users to think within their specialty or use their experience to propose solutions. This inertia could be overcome by using generic principles that are not specific to any domain, and by using TRAC the project manager would be able to explore construction performance solutions in areas of knowledge other than his own.

It should be emphasized that the above list of principles are broad, general, and not related to a specific organization or category of construction projects. Therefore, the construction organization can modify the above-proposed principles by removing, or adding new principles. In order to make corrections, each organization or user must look into and organize the accumulated specific industrial experience, solution methodologies used to solve past similar problems, and lessons learned. Also, technical/project management literature, journals, case studies, and the project manager's own professional experience could be additional sources of information.

5.1.4.5 The Performance Contradiction Matrix (PCM)

After having identified above the project/construction management sub-principles under each of the 40 TRIZ principles, this section introduces the idea of a performance contradiction matrix. Chapter 2 proposed eight generic objectives or performance indices for any construction project. Objectives that are considered for enhancement are in the vertical matrix column and those objectives that get worse are placed in the horizontal row. Objectives in the horizontal row are identical to those in the vertical column. To display all possible contradictions among the eight project performance indices, an 8x8 Project Performance Contradiction Matrix similar to the 40x40 Technical Contradiction Matrix of Altshuller, is proposed as shown in Table 5.4.

Table 5. 4 Project Performance Conflict Resolution Matrix

	Worsening Index → **Improving Index** ↓	**Cost Performance**	**Schedule Performance**	**Billing Performance**	**Profitability Performance**	**Safety - Total Recorded Incidents**	**Field Construction Re-work**	**Project Team Satisfaction**	**Client /Owner Satisfaction**
	Index	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	**Cost Performance**	+	1,2,9						
2	**Schedule Performance**		+			8,15	1,5,15		
3	**Billing Performance**			+					
4	**Profitability Performance**				+				
5	**Safety - Total Recorded Incidents**					+			
6	**Quality - Field Construction Re-work**						+		
7	**Project Team Satisfaction**							+	
8	**Client /Owner Satisfaction**								+

In some cases, project managers resort to trade-offs and compromise between the project objectives and consequently do not achieve good performance results. In very few cases, the project manager provides a solution without compromise. The idea behind this matrix is that most current problems are identical to past ones and that some companies or project managers have solved the majority of these performance problems sometime in the past. If only later project managers had the knowledge and recommendations of earlier project managers, solutions to construction performance problems could have been identified more efficiently. Any construction organization can use the proposed matrix as a starting point or can start to populate its own Contradiction Matrix using its own accumulated knowledge and experience as well as experience of other industries. This could help the company to derive most of the solutions from its own matrix. The Performance Contradiction Matrix (PCM) shown in Table 5.4 should consolidate the lessons learned and knowledge of the construction organization. It is also an effective method of documenting lessons learned. It is an effective tool for use by construction organizations in resolving project and construction-related performance conflicts while avoiding trade-offs. It should be noted that the matrix shown in Table 5.4 is only an initial draft and is partially populated for demonstration purposes. The matrix needs to be completed and validated by prospective users prior to implementation.

It is recommended that users first try to adopt the principles or concepts proposed by the Contradiction Matrix. If these do not help, the next option is to go through the remaining principles. Users should note that the suggested principles could generate the most promising plans or ideas for resolving a performance contradiction. When the suggested principle is viable but generates a secondary conflict, the user should not reject it but attempt to resolve it using the same approach. The following two alternatives can be used for resolving a performance contradiction:

1. Using the Performance Contradiction Matrix to identify the most effective principles.
2. Reading through each of the 40 identified principles and their associated sub-principles and selecting the most adequate.

5.1.4.6 The TRAC Process

The TRAC process is very similar to TRIZ process and allows users to follow a simple 7-steps approach to solve performance contradiction problems. The process is carried whenever there is a need to develop corrective action plans. The TRAC approach to performance problem solving can be described as follows:

- **Step 1: Identify the "Performance Problem"**

  The first step is to figure out the performance problem by identifying the origin of the problem and the elements that compose the performance system. Also, the interdependencies between the project's attributes need to be identified. We need to list all performance trade-offs that might lead to compromises.

- **Step 2: Formulate the "Specific Performance Contradiction"**

  The performance problem needs to be restated in terms of performance contradictions. All performance conflicts among the project objectives that might lead to trade-offs need to be listed. This step should answer the following question:

  Could improving one performance aspect (e.g. labor cost) to solve a performance problem (e.g. low labor productivity) cause other performance aspect (e.g. schedule and quality) to deteriorate?

  Go to Step 3 if you want to use the Performance Contradiction Matrix. Go to Step 6 if you want to read every principle and choose the most appropriate one.

- **Step 3: Transform the Specific into a "Generic Performance Contradiction"**

  There are eight *standard* conflicting performance attributes as shown in Table 5.4. The specific performance contradictions identified in step 2 have to be transformed into the standard or generic performance contradictions. First choose the closest performance index that needs to be improved. Then find the closest index that will deteriorate when the first index is enhanced (e.g. conflict between cost and schedule or cost and quality). State the standard performance conflict that will serve as an input to the Performance Contradiction Matrix.

- **Step 4: Search for a "Generic Solution"**

  After the performance contradiction is stated in step 3, the 40 principles and the matrix become useful. To find which performance resolution principles to use, use the Performance Contradiction Matrix displayed in Table 5.5. The Matrix of Contradictions lists the eight project performance indices on the X-axis (Deteriorating Index) and Y-axis (Improving Index). The intersecting cell provides a list of generic performance principles that are appropriate to the generic contradiction at hand.

- **Step 5: Transform the "Generic" into a "Specific Solution"**

  Based on the generic principles proposed by the matrix, filter the applicable principles and modify them or make them specific for the project. Do not reject any principle, but make a serious attempt to implement it. If all the suggested proposals are completely not applicable, go to step 2 and re-formulate the performance contradiction. Otherwise go to step 7.

- **Step 6: Read the 40 Principles**

  Read each of the 40 principles and their associated sub-principles and select the applicable ones. If you could not find appropriate principles to resolve the conflict go to step 2 and re-formulate the performance problem. Otherwise go to step 7.

- **Step 7: Identify the Corrective Action Plans**

  Transfer the various specific principles into workable corrective action plans. Furthermore, the project manager needs to prioritize the plans and should assign a time framework and responsible person for each plan.

The above procedure is shown in Figure 5.3.

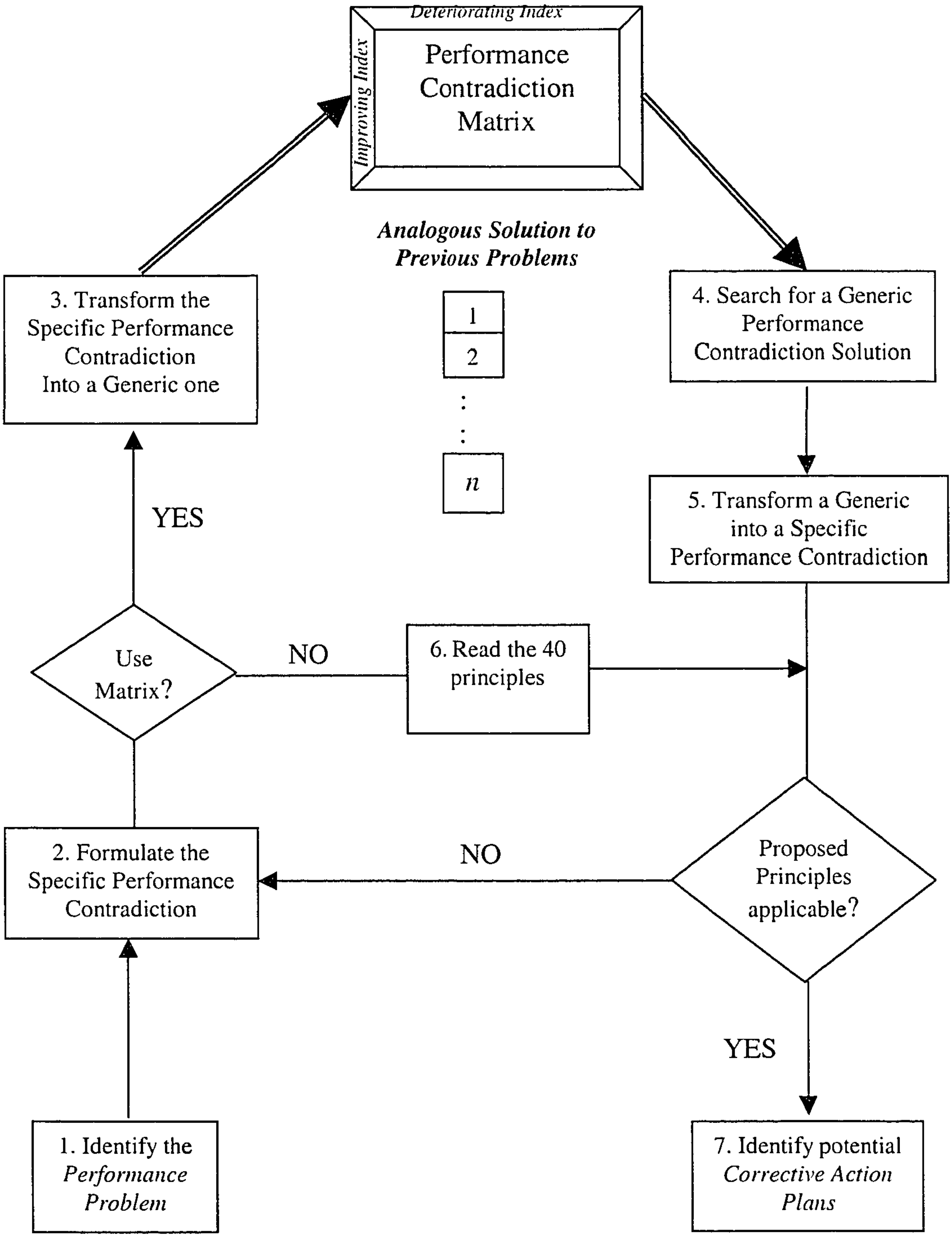


Figure 5. 3 TRAC process flowchart for performance problem solving

5.1.4.7 TRAC features

Based on above, it can be stated that TRAC satisfies the following characteristics:

1. Systematic procedure to solve construction performance contradictions.
2. Acts as a guide and helps the user converge to a proper corrective action from a broad solution space. It will limit the user's search to a narrow framework as shown in Figure 5.4.
3. Contains a wide range of repeatable and reliable conflict resolution principles drawn from the body of knowledge and from past experience lessons learned.
4. Flexibility of modifying, adding, and expanding the body of knowledge as represented by the principles and matrix.

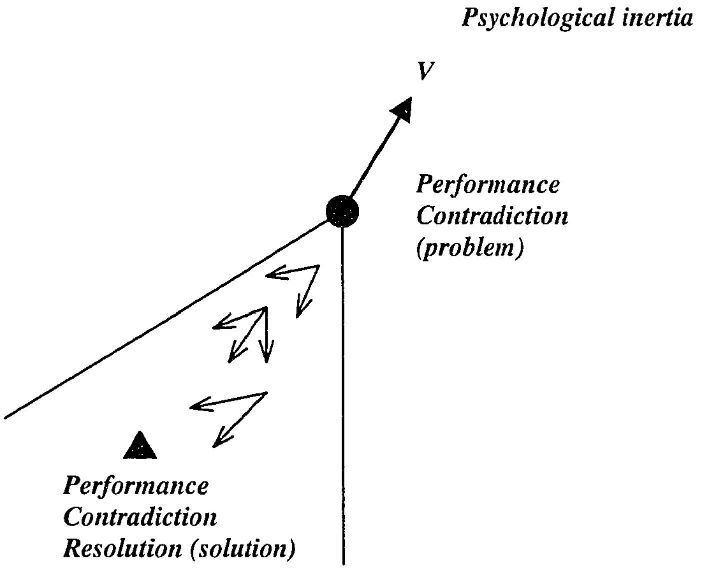


Figure 5. 4 Diagram showing the TRAC search method

5.1.4.8 Validation of the Project Performance Contradiction Matrix

It should be noted that the contradiction matrix shown in Table 5.4 is not validated and the objective of this chapter is to initiate the idea of a performance contradiction matrix. Three cells in the matrix have been populated using the author's personal experience in order to demonstrate its use and functionality and may be used as a starting point. A complete, comprehensive, and validated matrix needs to be developed for the construction industry, and could be an interesting subject for future research. Moreover, the conflict resolution principles and the performance contradiction matrix should be validated by every implementing organization and it should stand the test of time.

5.1.5 Reconciling Construction Performance Conflicts using the TRAC methodology: Illustrations

The objective of TRAC is to offer a common means of explicitly defining a performance conflict and resolving it. TRAC is a simple but effective approach to systematically minimize conflict among the performance indices. Although some experienced project managers can be successful in solving construction performance problems without compromise, the classic approach to resolve performance conflicts has been using trade-offs. In contrast to trade-off scenarios or handling a contradiction by choosing one preferable plan in the conflict, a solution based on TRAC aims to solve (or at least minimize) the contradiction by presenting a new plan in which the improvement of one performance index is not accompanied by deterioration of the other index. This is achieved by avoiding *performance tradeoffs* and reaching what is called a win-win situation.

It should be noted that the principles proposed in the matrix are not guaranteed to solve the contradiction at hand. The proposed principles are generated based on past lessons taken from past identical situations and considered to be highly probable but not certain. The following cases will demonstrate the use of TRAC methodology as outlined in the previous section to resolve performance conflicts.

Case A: Fabrication of Structural Steel

A contradiction between cost and schedule is evident in the supply of structural steel as illustrated in Figure 5.5. The need to reduce the production cost of steel by selecting a country with low cost of labor requires placing the order way ahead of time when possibly the final design is not complete. As a result, the order will not include the exact required quantities of steel. Although the action of placing an early order of steel will reduce the material cost, it will increase the risk of not having all material delivered to site on time. This performance conflict between structural steel fabrication cost and the timely delivery of steel will lead to sub-optimal overall project performance. On the other hand, placing a late order with a local manufacturer will guarantee on-time delivery of material but will increase the cost of material.

To resolve the conflict between project cost and schedule performances, TRAC 7-steps process is used to guide the decision maker in selecting a project management principle/s or approach that would reduce the negative impact of contradiction on the overall project performance by avoiding the *performance tradeoff.*

TRAC Process:

- **Step 1: Identify the "Performance Problem"**
  Based on the above problem description, the performance trade-off is between two competing plans: (A) fabrication of steel by an overseas manufacturer at a competitive cost, and (B) fabrication of steel by a local manufacturer to guarantee timely delivery of material.

- **Step 2: Formulate the "Specific Performance Contradiction"**
  The performance conflict is between fabrication cost of structural steel and its delivery schedule. Adopting plan (A) will increase the fabrication cost performance (lower fabrication cost) but decreases the chance of timely delivery or schedule performance. Implementing plan (B) will decrease the fabrication cost performance (higher cost) but enhances the schedule performance. The specific contradiction is shown in Figure 5.5.

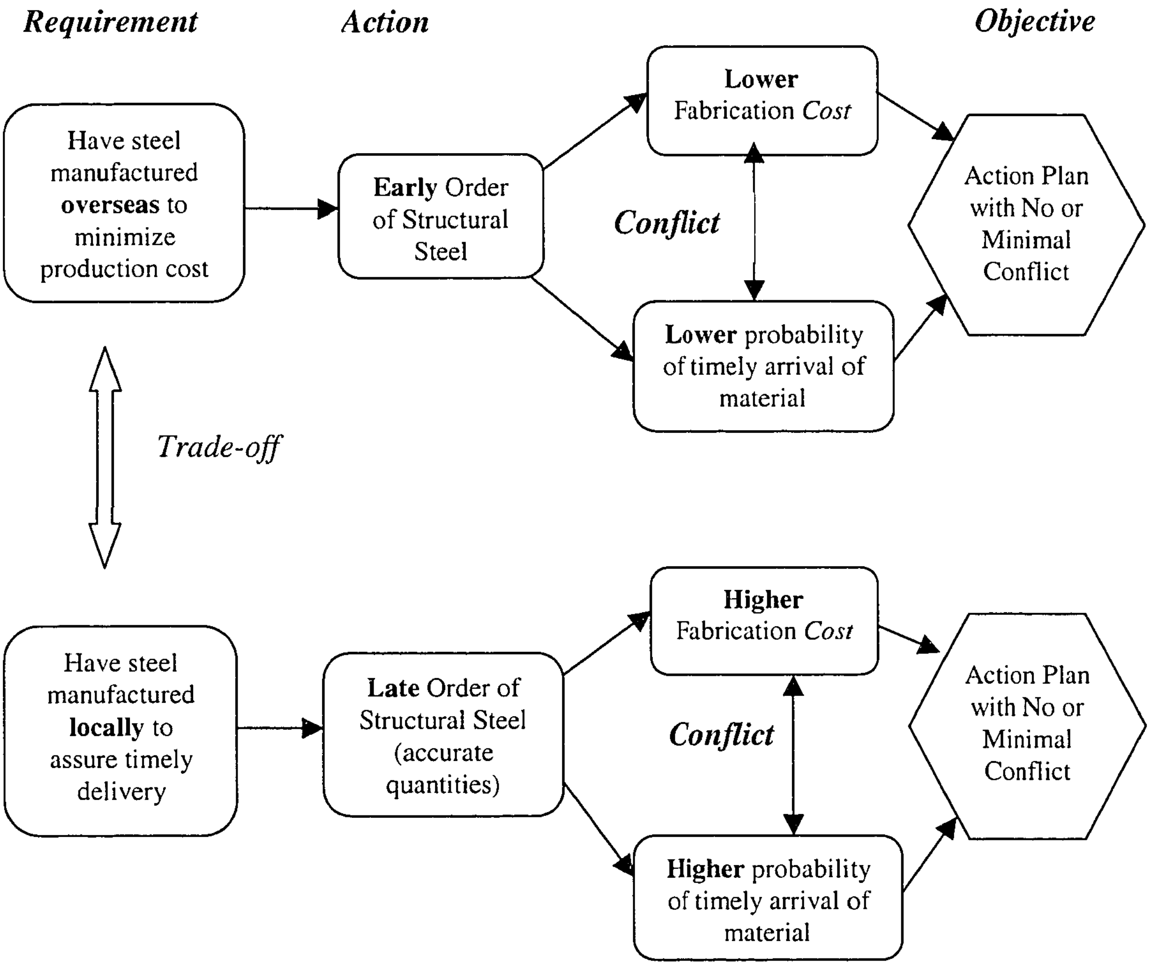


Figure 5. 5 Fabrication of Structural Steel Specific: Contradiction Diagrams

- **Step 3: Transform the Specific into a "Generic Performance Contradiction"**

  The specific contradiction could be represented as a conflict between two standard project attributes, namely between *Cost (improving index)* and *Schedule (deteriorating index).*

- **Step 4: Search for a "Generic Solution"**

  After the generic performance contradiction is stated in step 3, the 40 principles and the matrix in Table 5.4 can be used. In this case, the *improving* index on the y-axis is Cost and the *deteriorating* index on the x-axis is Schedule. The intersecting cell (1,2) provides three generic principles that are candidates to solve the conflict as shown in Table 5.5.

Table 5. 5 Project performance conflict resolution table – Case A

Action	**Performance Contradiction between Indices**	**Coordinates in Matrix**	**Suggested Generic Principles**	**Name of Principle (s)**
Early/later purchase of structural steel	Schedule and Cost performance indices	(1, 2)	1	-Segmentation

- **Step 5: Transform the "Generic" into a "Specific Solution"**

Based on the generic performance resolution principles proposed by the matrix, the following sub-principle is adequate or applicable to minimize the specific contradiction at hand:

-TRAC Principle 1-A: Divide an object into independent parts.

- *Divide a Purchase Order (quantity wise) into smaller orders.*
- *Divide a Purchase Order (quantity wise) into smaller orders.*

- **Step 7: Identify the Corrective Action Plans**

The specific principle proposed in Step 5 is then translated into the following workable corrective action plan.

1. Place early order to manufacture an initial quantity of steel in a low cost country (based on preliminary bill of material and before design is finalized).
2. The Place late order to manufacture the remaining and final quantity of steel from a local manufacturer (based on final bill of material and final design).

This case illustrates a common material procurement issue and emphasizes the importance of understanding the impact of material purchase decisions on the overall project performance. It also demonstrates how the so-called win-win principle could be achieved.

Conflict Resolution: The proposed corrective action plan managed to minimize the conflict by getting a good price by early ordering the bulk of material while assuring a timely delivery by ordering the remaining material form a local fabricator.

Case B: The impact of crashing the construction duration on safety performance

At many points in the life of a project, construction durations for some work packages are reduced to compensate for the late start due delays in engineering or procurement. In such cases, a conflict between Safety and Schedule is very probable as illustrated in Figure 5.6. The need to reduce the construction duration will lead to activity crashing and consequently the safety performance could decrease as the probability of having more accidents increase due to activities being executed in parallel and labor working in congested areas. This performance conflict between safety and schedule will decrease the overall project performance.

To resolve the conflict between project cost and schedule performances, TRAC 7-steps process is used to guide the decision maker in selecting a principle/s or approach that would reduce the negative impact of contradiction on the overall project performance by avoiding the *performance tradeoff.*

TRAC Process:

- **Step 1: Identify the "Performance Problem"**

  In this case, the performance trade-off is between two competing courses of action: (A) Crashing the schedule to compensate for delay in material delivery or engineering, and (B) keeping the original duration of construction activities and running the risk of not completing the project as planned.

- **Step 2: Formulate the "Specific Performance Contradiction"**

  It is very obvious that the performance conflict is between the duration of work and the level of construction safety. Crashing the schedule (Plan A) will increase the schedule performance but decreases the safety performance. Implementing Plan (B) or keeping the original durations will decrease the schedule performance but will not risk safety performance. This contradiction is shown in Figure 5.6.

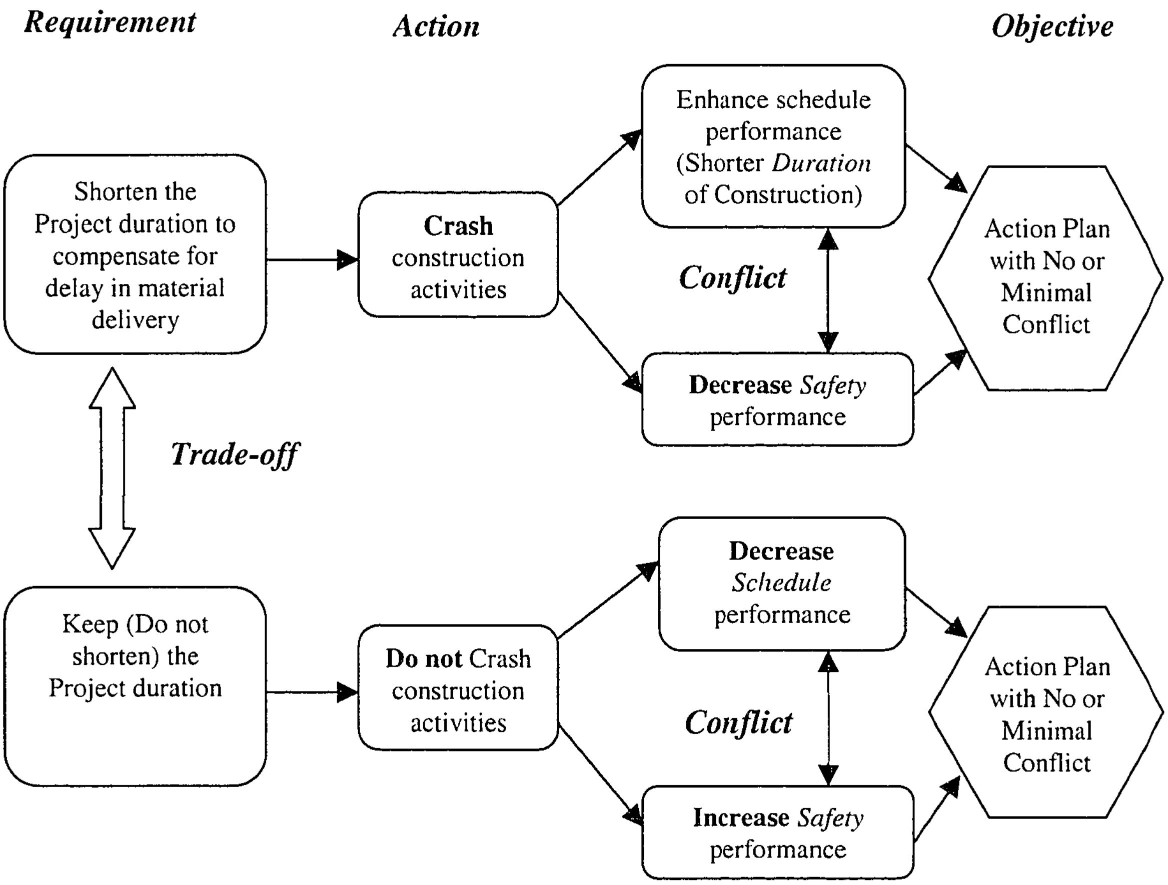


Figure 5. 6 Schedule-Safety Specific Contradiction Diagrams

- **Step 3: Transform the Specific into a "Generic Performance Contradiction"**

  The specific contradiction could be represented as a conflict between two standard project attributes, namely between *Schedule* (*improving index*) and *Safety (deteriorating* index).

- **Step 4: Search for a "Generic Solution"**

  After the generic performance contradiction is stated in step 3, the 40 principles and the matrix in Table 5.4 can be used. In this case, the *improving* index on the y-axis is Schedule and the *deteriorating* index on the x-axis is Safety. The intersecting cell (2,5) provides two generic principles that are candidates to solve the conflict as shown in Table 5.6.

Table 5. 6 Project performance conflict resolution table – Case B

Action	Performance Contradiction between Indices	Coordinates in Matrix	Suggested Generic Principles	Name of Principle (s)
Shorten/keep Project Duration	Schedule and Safety performance indices	(2, 5)	8, 15	-Counterweight -Dynamics

- **Step 5: Transform the "Generic" into a "Specific Solution"**

Based on the generic performance resolution principles proposed by the matrix, the following sub-principles are adequate or applicable to minimize the specific contradiction at hand:

- TRAC Principle 8-B: Compensate for the weight of an object with aerodynamic or hydrodynamic forces influenced by the outside environment.

  - *Use automation in construction and technology to make some risky activities safer to perform and be executed in less time.*

- TRAC Principle 15-C: If an object (or process) is rigid or inflexible, make it movable or adaptive.

  - *Employ flexible project staff (e.g. using temporary workers, overtime, double shifts, and multi-functional personnel).*

- **Step 7: Identify the Corrective Action Plans**

The specific principle proposed in Step 5 is then translated into the following workable corrective action plan.

1. Construction automation (e.g. use of robotics & equipment) can minimize the manpower requirement and duration to do the work and can lower the chance of labor getting hurt.

2. Use of overtime hours or double shifts could flatten the manpower histogram and ease site congestion. This measure could effectively reduce the conflict with little expense.

Conflict Resolution: The suggested corrective activities reduce the conflict by enhancing the schedule (without crashing durations) while assuring a safe construction practice. This was possible by removing the sources of conflict like congested work areas and use of equipment instead of labor-intensive construction methods.

Case C: Crashing the construction duration of cast-in-situ concrete manholes

In almost all projects, construction durations are reduced to compensate for delay in engineering, delay in delivery of material, etc. In this case, a delay in the issue of drawings for the concrete manholes requires crashing the construction schedule to maintain the original planned completion date. A contradiction between schedule and quality of work as measured by the Construction Field Rework Index (CFRI) will probably arise due to shortening the construction period. This is due to the fact of constructing without having proper time for planning the work and later for inspecting it in addition to site congestion thus resulting in field rework and in-efficiency. In other words, enhancing the schedule could make the quality of work deteriorate and a conflict between schedule and quality is evident as illustrated in Figure 5.7. This performance conflict between schedule and quality will decrease the overall project performance.

To resolve the conflict between project cost and schedule performances, TRAC 7-steps process is used to guide the decision maker in selecting a project management principle/s or approach that would reduce the negative impact of contradiction on the overall project performance by avoiding the *performance tradeoff.*

TRAC Process:

- **Step 1: Identify the "Performance Problem"**

  Based on the above problem description, the performance trade-off is between two competing plans: (A) crashing the concrete manholes construction schedule, and (B) keeping the original durations to avoid field rework.

- **Step 2: Formulate the "Specific Performance Contradiction"**

  The performance conflict is between the concrete manholes schedule and its quality. Adopting option (A) increases the schedule performance but increases the probability of re-work. Implementing option (B) decreases the schedule performance but maintains good quality performance. The specific contradiction is shown in Figure 5.7.

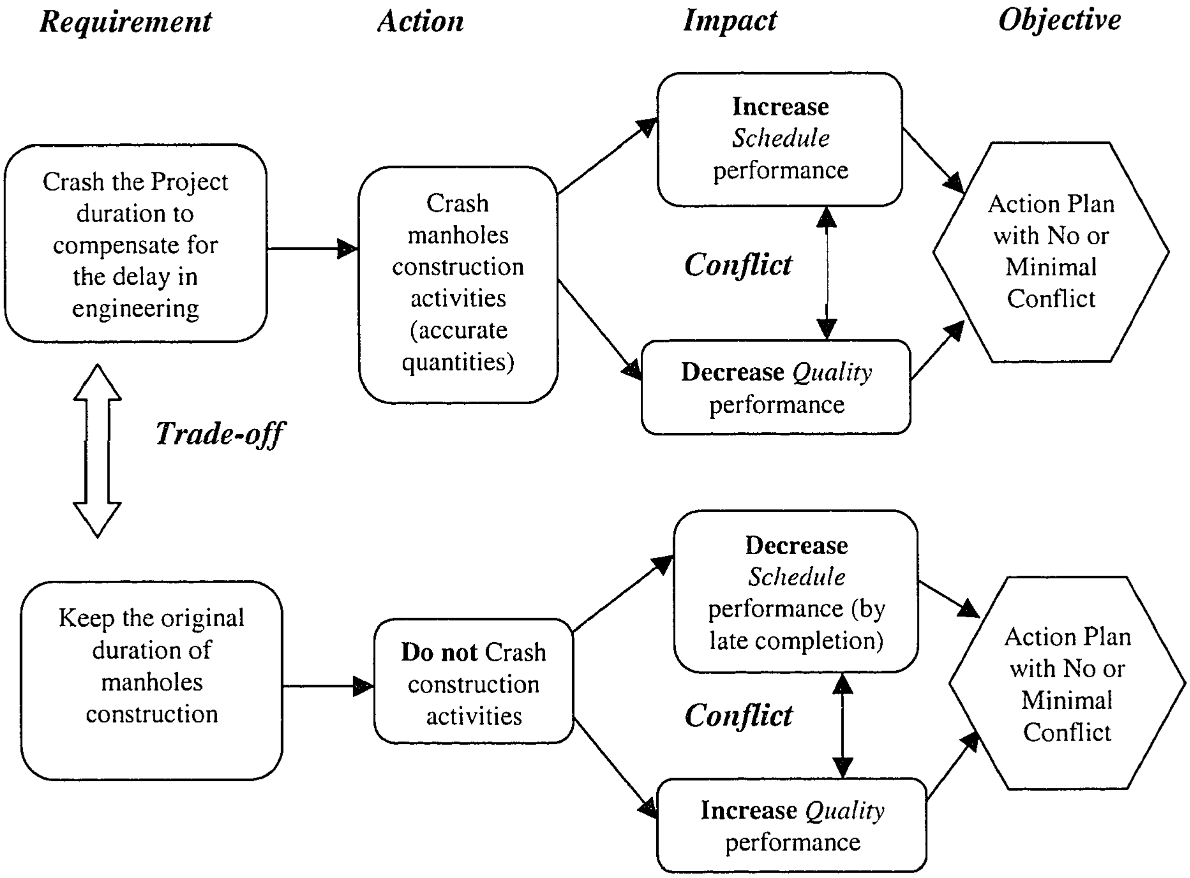


Figure 5. 7 Schedule-Quality Performance Contradiction Diagrams

- **Step 3: Transform the Specific into a "Generic Performance Contradiction"**

  The specific contradiction could be represented as a conflict between two standard project attributes, namely between *Schedule (improving index)* and *Quality (deteriorating index).*

- **Step 4: Search for a "Generic Solution"**

  After the generic performance contradiction is stated in step 3, the 40 principles and the matrix in Table 5.4 can be used. In this case, the *improving* index on the y-axis is Schedule and the *deteriorating* index on the x-axis is Quality. The intersecting cell (2,6) provides three generic principles that are candidates to solve the conflict as shown in Table 5.7.

Table 5. 7 Project performance conflict resolution table – Case C

Action	**Performance Contradiction between Indices**	**Coordinates in Matrix**	**Suggested Generic Principles**	**Name of Principle (s)**
Shorten construction of manholes duration	Schedule and Quality performance indices	(2, 6)	1, 5, 15	-Segmentation -Consolidation -Dynamics

- **Step 5: Transform the "Generic" into a "Specific Solution"**

Based on the generic performance resolution principles proposed by the matrix, the following sub-principles are adequate or applicable to minimize the specific contradiction at hand:

-TRAC Principle 1-A: Divide an object into independent parts.

- *Use project segmentation where by the work content is divided into several sub-projects or segments so that the same set of activities is performed on each segment. Executing work in parallel can reduce the project duration.*

-TRAC Principle 5-B: Consolidate in time homogeneous operations.

- *Use of "concurrent engineering" or the simultaneous progress of activities to expedite the project.*
- *Offsite "Prefabrication" to advance the construction.*

-TRAC Principle 15-C: If an object (or process) is rigid or inflexible, make it movable or adaptive.

- *Employ flexible project staff (e.g. using temporary workers, overtime, double shifts, and multi-functional personnel).*

- **Step 7: Identify the Corrective Action Plans**

The specific principle proposed in Step 5 is then translated into the following workable corrective action plan.

1. **Use Project Segmentation**: Dividing the work into separate construction work packages and awarding them to various sub-contractors will allow execution of work in parallel thus reducing the construction duration.

2. **Use Concurrent Engineering**: The simultaneous progress of engineering, procurement, and construction activities will allow earlier start of construction work and consequently allowing enough time for proper planning and execution.

3. **Use Pre-cast Concrete Construction**: Use of Pre-cast manholes instead of cast-in-situ will reduce the construction period and produce better quality.

4. **Use of overtime hours or double shifts**: This can minimize the construction duration and flatten the daily manpower histogram without overlapping site activities (a major cause for rework and inferior quality).

Conflict Resolution: The proposed corrective action plan can reduce the conflict by enhancing the schedule (without crashing durations) while assuring a good quality of work and minimal field re-work. This is achieved by removing the sources of conflict like congested work areas and traditional construction methods.

Case D: Award of a Modules Fabrication Contract

A contradiction between Schedule and Cost arises due to awarding an off-site module fabrication contract as illustrated in Figure 5.8. The need to award the module fabrication work through competitive bid tendering process (usually 8-12 weeks) will guarantee the award of the work to the lowest fabricator but at the same time with could delay the award of the contract, the procurement of long lead items (e.g. the low temperature steel used to build the modules) and consequently the fabrication period of the modules. On the other hand, avoiding the normal bidding cycle to save time by sole sourcing the work (reducing the bid cycle time), will allow early procurement of long lead items by the fabricator but will not lead to a competitive price. This performance conflict between cost and schedule will lower the overall project performance.

To resolve the conflict between project cost and schedule performances, TRAC 7-steps process is used to guide the decision maker in selecting a project management principle/s or approach that would reduce the negative impact of contradiction on the overall project performance by avoiding the *performance tradeoff.*

TRAC Process:

- **Step 1: Identify the "Performance Problem"**

  Based on the above problem description, the performance trade-off is between two competing plans: (A) Awarding the contract by competitive bidding to obtain competitive cost, and (B) Sole sourcing the fabrication work thus shortening the contract bidding cycle but at the expense of cost effectiveness.

- **Step 2: Formulate the "Specific Performance Contradiction"**

  The performance conflict is between fabrication cost of modules and its delivery schedule. Implementing plan (A) lowers the cost of fabrication but increases the bid cycle time and consequently delay the fabrication completion time. Implementing plan (B) leads to higher fabrication cost but expedites the award of the contract and allows early procurement of the long lead raw material (low temperature steel) and consequently advances the modules fabrication completion time. The specific contradiction is shown in Figure 5.8.

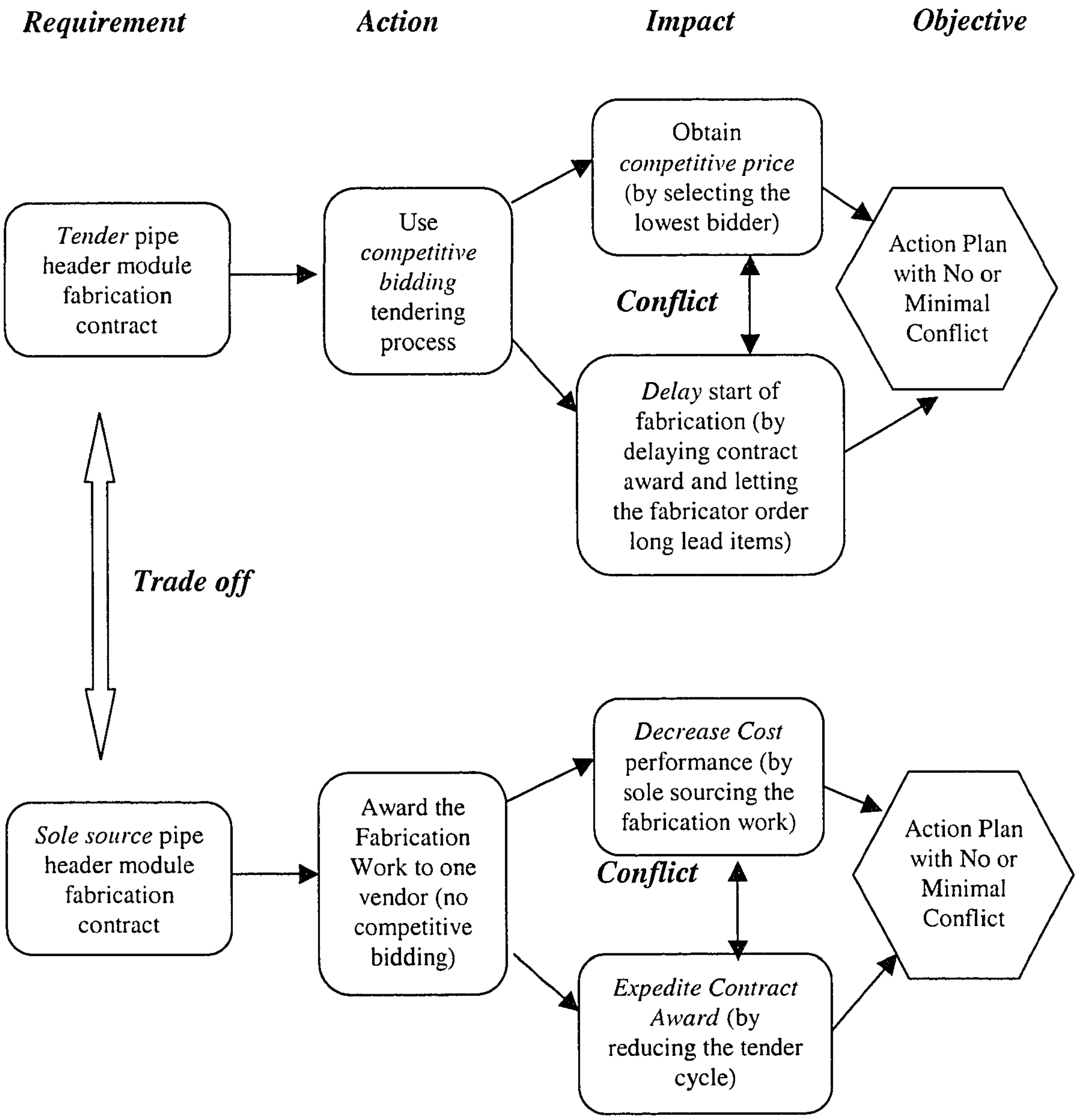


Figure 5. 8 Modules Fabrication Contract: Contradiction Diagrams

- **Step 3: Transform the Specific into a "Generic Performance Contradiction"**

  The specific contradiction could be represented as a conflict between two standard project attributes, namely between *Cost (improving index)* and *Schedule (deteriorating index).*

- **Step 4: Search for a "Generic Solution"**

  After the generic performance contradiction is stated in step 3, the 40 principles and the matrix in Table 5.4 can be used. In this case, the *improving* index on the y-axis is Cost and the *deteriorating* index on the x-axis is Schedule. The intersecting cell (1,2) provides three generic principles that are candidates to solve the conflict as shown in Table 5.8.

Table 5. 8 Project performance conflict resolution table – Case D

Action	**Performance Contradiction between Indices**	**Coordinates in Matrix**	**Suggested Generic Principles**	**Name of Principle (s)**
Competitive tendering process to award the modules fabrication contract	Schedule and Cost performance indices	(1, 2)	2 9	-Extraction -Prior Counteraction

- **Step 5: Transform the "Generic" into a "Specific Solution"**

Based on the generic performance resolution principles proposed by the matrix, the following sub-principles are adequate or applicable to minimize the specific contradiction at hand:

-TRAC Principle 2-A: Extract the "disturbing" part or property from an object.

- *Identify and extract the critical items from scope of work in order to remove the "disturbance" or criticality.*

-TRAC Principle 9-B: Create beforehand actions in an object that will oppose known undesirable working stresses later on.

- *Early order of long lead items.*

- **Step 7: Identify the Corrective Action Plans**

The specific principles proposed in Step 5 are then translated into the following workable corrective action plan.

1. Extracting or removing the scope of work that will impact the completion of fabrication. In this case, extracting the supply of low temperature steel, being a long lead item, form the scope of the fabricator.
2. Early procurement of long lead items. The owner or EPC contractor will order the steel before the award of the fabrication contract and will deliver (free-issue) the material to the fabricator's yard.

Conflict Resolution: The recommended plan will enable the contractor to award the work by competitive bidding (to get the best price) while not jeopardizing the schedule through him purchasing the long lead items and free-issuing them to the successful fabricator.

5.1.6 Advantages of TRAC

TRAC reduces construction management risk by providing construction managers a problem-solving tool, which could help them, *if competent*, solve construction performance related problems. TRAC will assist or guide the project manager to select and propose corrective action measures that generate minimal conflict among the competing performance indices in a systematic and timely fashion. This input can be fed to the corrective action GA optimization model as presented in chapter 4. In addition, the implementation of TRAC by construction organizations can have many advantages and benefits. In particular, TRAC could:

- Help the construction management team in the Corrective/Preventative Action process by hopefully accelerating the search for solutions and consequently saving time and energy. In addition TRAC helps its users overcome some pre-conceived notions. TRAC is based on the assumption that the resolution of conflicts and contradictions between the competing performance indices could be structured and that good solutions to performance problems avoid tradeoffs.
- Facilitate progressive thinking and creativity within the project/construction management team and train them to look at problems in an innovative way as well as make them think outside the box.
- Enhance the quality and quantity of the generated corrective action or solutions.
- Help contracting organizations store company knowledge and conflict resolution principles systematically in one database. In many organizations, the lessons learned in construction projects are buried in the heads of the project team members. Because construction teams move from project to another or leave the company, a great amount of experience is usually lost. TRAC is one mean of organizing and managing such valuable knowledge.

5.1.7 Conclusion and observations

During the process of construction, project managers, using only their experience, can always find approximate solutions to simple conflicting performance problems. However, very few project managers can easily, and under tight time framework, develop solutions for complex problems. As a result, there is a need to develop a heuristic method or mechanism to attain effective solutions to complex construction performance problems in a timely manner. Towards this end, this study presented a new model for performance problem solving to assist project managers in their corrective action exercise. The model is based on the "theory of inventive problem solving" TRIZ in general and the Technical Contradiction Matrix in specific. Although TRIZ was originally developed to solve technical contradictions, it is has been applied to provide innovative solutions to problems in non-technical fields. The presented study shows that the analogy between technical contradictions and construction performance contradictions is valid.

It has been mentioned above that construction contractors should test and refine the generic performance resolution model and not take it for granted. Users can evaluate the proposed TRAC methodology by evaluating TRAC recommendations against the company's own accumulated knowledge, lessons learned, and the recommendations of its project managers.

Future research needs to be done to complete and validate the Performance Contradiction Matrix by analyzing many case studies and lessons learned from past projects. Nevertheless, the fact that the number of principles is relatively small (40) renders the option of using the principles without guidance from the contradiction matrix a feasible option. However, a computerized system for storage and retrieval of information for solving performance problems is highly recommended.

Using the proposed model for resolving performance contradictions provides a structured approach that guides project managers to propose corrective action that leads to minimal conflict and ultimately to better project performance. Resolving contradictions is the way for generating good and practical corrective action plans that would enhance project performance. The proposed model provides companies a mechanism to create and store new knowledge for use by all project management staff. To conclude this study, the following observations are made:

Typical Obstacles against the use of TRAC

The application of TRAC by construction organizations will definitely pay in the long run but its adoption by some contractors could face few human-related obstacles some of which are:

- *Lack of top management support:* Senior management is not committed to invest time and money for training and implementation.
- *Lack of time*: Project managers are too busy fighting problems to learn new techniques to solve problems.
- *Use of traditional systems and resistance to change*: The use of TRAC will be discouraged if construction organizations insist on using their traditional project management systems. This does not mean that TRAC will replace traditional systems, but on the contrary will supplement these systems.

Limitation of the proposed TRAC methodology

The objective of the proposed methodology is to provide users with some guidance to solving construction performance problems. They do not guarantee conflict resolution and do not provide users complete and workable solutions. The objective of this framework is to accelerate the search for a solution in the right direction and not to generate "ready to use" corrective plans. Project managers are expected to utilize their experience and judgment along with the proposed principles to produce solutions for the performance contradiction at hand. As defined above, TRAC is a user-oriented methodology and the human element or the project manager experience is fundamental in this regard.

Necessary Qualities for TRAC user

Based on above, it is obvious that TRAC will not provide a solution but guide the problem solver (e.g. project manager) to the appropriate solution. It is necessary for a project manager to know the scope of work and project environment and use his experience and judgment. In addition, potential TRAC users have to:

- *Learn TRAC methodology* and how to apply it to resolve contradictions in construction performance.
- *Have good knowledge* of relevant project management and construction practices.
- *Be open to new ideas* and willing to use a wide range of techniques and methods.

Although TRAC concept is based on the innovative TRIZ theory, it can be considered as a simple and effective tool to deal with performance conflict problems and evaluate corrective actions. The author's experience in managing construction projects tells that implementing corrective action plans could be more difficult than finding them. Implementation of effective and feasible plans is what contributes to the project success.

5.2 Introduction to an Agent-based Project Performance Management Framework (APPM)

5.2.1 Introduction

Current project controls tools are still based on separate disconnected models for controlling cost, schedule, safety, quality, and profitability. These traditional project controls methods are not sufficient for managing the many attributes of project performance in an effective manner. They do not consider all the performance indices as proposed in the IPPM model in Chapter 2, the interactions between the indices, and the necessity for distributed performance measurement. Moreover, they do not provide adequate feedback of performance status to the right agents (users or software) at the right time through out the project construction phase. Also, the current approaches to performance management are reactive and consequently may not lead to good solutions. If, however, plans are coordinated and their impacts on the performance indices are assessed prior to implementation, then better solutions can be found. To overcome these problems, this thesis developed a new methodology for the measurement, forecasting, and optimization of performance. The new methodology depends on a computer platform that facilitates collaboration between the multi-disciplinary performance elements in a construction project. It also needs a computer infrastructure to facilitate the flow of information across the heterogeneous set of computer programs. The currently implemented Information Technology (IT) methods cannot completely solve the problems posed by the use of heterogeneous software tools and the lack of effective collaboration tools. On the other hand, centralized project management (e.g. all information are stored and processed in one system) makes the exchange of information redundant and unreliable. Mistakes are less likely if project data is stored only once and are accessed remotely by the team members. In other words, the successful implementation of the new methodology requires a flexible, dynamic, distributed, and intelligent computer framework. Distributed artificial intelligence (DAI), which is usually implemented in the form of intelligent agents, offers an innovative approach to overcome this challenge.

Distributed Integrated Project Performance Management requires process coordination between many departments (e.g. safety, quality, cost, finance, and planning), engineering disciplines (e.g. civil, mechanical), and computer tools (e.g. scheduling programs, financial software). The coordination process is very complex since it involves a heterogeneous mix of software and users passing messages and setting up corrective action plans. A *model of coordination*, agreed upon by human and software agents, is thus necessary for distributed controls.

Most often, construction management decisions are often taken without considering the interdependency among the various project aspects. The decisions are optimized locally within the individual project departments thus leading to sub-optimal global outcome. It should be noted that decision support tools exist in almost every project for local decision-making, e.g. scheduling computer program to measure schedule performance, another financial database program to capture costs and measure profitability, etc. These drawbacks in current systems were overcome by this research, which established a unified approach and an integrated system for performance management. The proposed model in this research explicitly captures the interactions among the various performance aspects of a project and provides an integrated methodology for decision-making. Now, a central computer integration of these various models and tools has many disadvantages and consequently there is a clear need for using innovative systems based on distributed artificial intelligence. Some of the disadvantages of centralized control architectures are:

- Organizational structure is not centralized.
- Relevant information is not available in a timely manner.
- Difficulty in adapting to dynamic project circumstances.
- Large computational overburden is placed in one location.

The aim of this research is to address this critical need by introducing the concept of *Multi-Agent Systems (MAS)* and its application for the management of project performance. The artificial intelligence area proposes software agent-based concepts that seem to be promising in handling our problem. Software agents are characterized by intelligence, collaboration, proactive behavior, and mobility, and thus are ideal to overcome the drawbacks of classical computer platforms, which use centralized database systems. Software agents react to the project performance states and pursue defined goals. One of the advantages of MAS is due to the cooperation between agents. This cooperation provides solutions to problems that cannot be solved by the centralized system.

This chapter will *introduce* an agent-based framework to facilitate the implementation of the integrated performance management model developed in this research. This framework establishes an infrastructure to support the distributed task interactions and to render the practical implementation of the above-proposed models by practitioners a viable option. In particular, this chapter aims to investigate the use of intelligent agents to facilitate communication, collaboration, and negotiation among the various project departments represented by agents. In the context of this study, agent-based negotiation is the process of resolving performance contradictions among impacted agents by increasing knowledge through the structured exchange of relevant information. This approach, which overcomes the problem of geographically distributed project performance departments, is new to construction performance management.

The main contribution of this study is to provide theoretical foundation for a functional multi-agent prototype system and it is only a first step towards the development of a comprehensive model.

This chapter first introduces the concept of distributed artificial intelligence, and multi-agent systems (MAS). It then reviews MAS applications in the construction industry. The rest of the chapter is organized as follows: Section 5.2.4 explains what makes (MAS) applicable to performance management. This is followed by a generic description of the proposed Agent-based Project Performance Management Framework (APPM). The chapter concludes with future research needs and a conclusion.

5.2.2 Distributed Artificial Intelligence (DAI) and Multi-Agent Systems (MAS)

Distributed Artificial Intelligence (DAI) is a sub-area of artificial intelligence that deals with modeling multiple interacting systems. The main component of any artificial intelligence application is a body of knowledge consisting of expert information, facts, procedures, models, and concepts. DAI is a methodology for controlling distributed and large-scale systems by decomposition. A large system is decomposed into a set of smaller but inter-connected subsystems, each of which is responsible for managing its domain and coordinating its activities with other sub-systems. It is similar to a group of experts cooperating together to solve a global problem that is challenging and decomposed. DAI methods can establish a robust framework through fast exchange of information, sharing of critical resources, and quicker response to changes.

The term multi-agent system (MAS) denotes an agent-based application of DAI. A MAS consists of a set of non-centralized and collaborating elements (agents) that act in an autonomous manner to reach an overall goal. O'Hare and Jennings (1996) provided this definition: "*a MAS is a network of problem solvers that work together to solve problems that are beyond their individual capabilities*". In a multi-agent system (MAS) intelligent agents interact to achieve their individual objectives as well their common objective through exchange of information, cooperation, and negotiation to resolve conflicts. These agents possess unique features like: autonomy, pro-activeness, reasoning capability, social ability (interaction with the user and other agents), and human-like features (e.g. beliefs, desires, intentions, and motivations).

Agents can be a piece of software, hardware, machine, or a human. In the context of this research we deal with software agents. A software agent is an agent that is implemented using computer software and can interact with its environment. This means that software agents are autonomous and can react to and communicate with other entities, including human users, machines, or other software agents existing in various environments and platforms. From this point on, the term *agent* will denote a *software agent.*

MAS originated from research in distributed artificial intelligence (DAI) (Ferber 1999), where the activities of a system are distributed among many parties for cooperative problem solving. In MAS, every agent has its own goal that may contradict with goals of other agents. Cooperative problem solving is achieved when a group of decentralized agents work together to achieve a common goal, which is project performance in our case.

The question is what makes a problem domain suitable for the use of multi-agent systems? Many researchers agree that MAS are best applicable to solve problems that are distributed in nature and require the use of artificial intelligence (Aylett et al. 1997).

The increasing interest in MAS research is due to the many advantages these systems have, including their ability to:

- Solve complex problems.
- Provide solutions to distributed problems.
- Allow for the interconnecting of multiple existing heterogeneous platforms and different programming languages.
- Tolerate uncertain information.

5.2.3 MAS applications in Construction Engineering and Management

There is very little research related to the application of multi-agent systems (MAS) to problems in the construction industry. Some work has been carried out at the Center for Integrated Facility Engineering (CIFE) at Stanford University (Kim and Paulson 2003). Outside the construction industry, the concept of *Multi-Agent Systems (MAS)* has been widely applied in many diverse areas ranging from process engineering to air-traffic controls. In the following section, the application of agents in the construction industry is reviewed.

Dzeng and Lin (2004) presented an agent-based system to help construction contractors negotiate with their suppliers via the Internet. The system, named C-Negotiators, uses software agents to facilitate negotiation and reach a final contractual agreement. Anumba et al. (2003) developed a multi-agent system framework for the collaborative design of light industrial buildings. In this case, agents try to automate the interaction and negotiation between the design team members. Kim and Russel (2003) developed a conceptual framework for an intelligent earthwork system to enhance the intelligence of construction equipment. The system is intended to automatically generate plans for construction equipment and provide means of cooperation between equipment. The implementation of the proposed system will improve worker safety, quality of work, and reduce project duration. Kim and Paulson (2003) presented an agent-based compensatory negotiation methodology to facilitate the distributed coordination of project schedule changes. This research helps sub-contractors coordinate their different schedules by working together toward better results. Ren et al. (2003) developed a multi-agent system to enhance the efficiency of construction claims negotiation. This system, named MASCOT, uses autonomous agents, representing project participants, which negotiate with each other to resolve construction claims. To overcome the problem of using heterogeneous design computer tools, Anumba et al. (2002) presented a prototype system using the agent technology to enhance the collaborative design of portal frame structures. Lees et al. (2001) proposed an agent-based approach to concurrent engineering and to assist in design collaboration across heterogeneous platforms. Yan et al. (2000) used multi-agent systems to support project management in a distributed environment. Project activities, resources, and specific project management tasks are represented as agents in a network. Petrie et al. (1999) presented a novel approach for managing complex distributed projects using agent-based systems. The study has demonstrated how the various phases of a project including design, planning, and construction can be distributed but coordinated by using a facilitating agent. Shtub (1995) addressed the issue of project controls in a distributed environment. The author developed a data structure to establish communication between distributed project management databases and software packages. The model is very useful for companies performing projects using a set of heterogeneous project management computer systems. Smith (1992) proposed an intelligent planning system for project management.

Although the above review is not exhaustive, it shows that there are no (MAS) application in the domain of construction performance and management and no commercial systems available for use by industry practitioners.

5.2.4 Research motivation for the application of MAS in Performance Management

There are many challenges facing the effective implementation of the integrated project performance management system described in this thesis. The first challenge is that the information across all the disciplines and departments of a construction organization is distributed, dynamic and heterogeneous in nature. The second challenge is due to the fact that the decision centers reside in different departments within the organization. For example, one department handles quality, where another department manages construction safety. Thirdly, the project departments, each representing a specific performance area, need to continuously communicate, exchange knowledge, and negotiate plans in order to resolve conflicts and find solutions. The answer for overcoming these challenges is to provide an adequate computer platform that is efficient, reliable, intelligent and capable of handling the problems posed by the proposed performance model. It is obvious, based on the above discussion, that a large monolithic system would be not adequate to overcome these challenges. It is believed that a system of autonomous agents would represent an appropriate model for the realization of the developed performance management system.

5.2.4.1 Why an Agent-based Approach?

In order to maintain competitive advantage and overcome the above-mentioned challenges, construction organizations need to invest in information technologies in general and in agent-based systems in particular. This is due to the fact that multi agent-based systems are particularly appropriate for problems that are dynamic, uncertain and distributed (Woolridge 2002). MAS can replicate interactions, within a certain problem domain, of several entities each having different and most probably conflicting objectives. An example of a problem domain is the construction performance optimization problem where the various project objectives interact and compete with each other. MAS, through fostering interaction between project objectives (represented by agents), can assist in resolving conflicts and consequently can achieve better performance.

Burmeister et al. (1997) suggest that MAS are appealing for describing complex systems. Aylett et al. (1997) justify the application of multi-agent systems to problems that are distributed in nature and require the use of artificial intelligence. The project performance system is a very sophisticated system that involves many parties that are geographically distributed and are implementing heterogeneous systems. Based on above, there are four situations under which agent-based methods can significantly contribute. All the three situations exist in the project performance problem domain as explained below:

- **The problem domain is geographically distributed and heterogeneous**: The project performance domain of almost any construction project is not limited to one physical location or system. In other words, the elements of performance are distributed across many geographical locations. For example, the financial performance could be handled by the company head office using one system, the safety performance managed on-site by a second system, and so on and for. In general, each performance attribute, within the same project, is managed by a specific organizational unit using a different computer system. Information pertaining to the various performance elements is also different in format.

- **The sub-systems change in a dynamic manner:** The project performance sub-systems like cost, schedule, safety, quality, etc., are continuously changing over time. For example the project schedule performance could change every week and could impact the performance of other sub-systems like cost or quality. Forecasted information in the performance model e.g. material cost, manpower requirements, site conditions, etc. are also changing continuously.

- **The sub-systems need to interact in a flexible manner**: The project sub-systems or objectives are contradictory in nature (e.g. quality vs. cost or cost vs. schedule) and need to communicate and coordinate in an extensive and continuous manner to resolve conflicts and to arrive at solutions that best serve the global goal and contribute to the overall project performance.

- **The system is complex**: The project performance management system proposed in this thesis is a complex one. The components of the system interact in a sophisticated way and are dynamic in nature.

5.2.4.2 Need for a distributed and heterogeneous system

Any attempt to model the many heterogeneous performance systems in one computer system to yield reliable and improved results is a very challenging task. Attempts to develop global "monolithic" computer programs, such as enterprise resource planning (ERP) systems, are not very successful due to the reasons discussed earlier. Based on this reality and the above facts, there is a clear need for a novel solution in the form of a highly distributed and heterogeneous system. A system that is capable of collecting and processing the dispersed information required for the proper implementation of the models (proposed in this research). The application of multi-agent systems to solve complex problems such as the optimization of construction performance is very promising. An additional reason for adopting an agent-based approach is that agents provide a more natural abstraction of the problem domain. The many features of agents are described below:

- *Robustness*: The distribution of control to a set of agents means that there is no single point of failure.

- *Efficiency*: Local distributed computation is less complex.
- *Scalability*: New agents can be easily added to a multi-agent system.
- *Economy*: Agent technology is capable of incorporating existing computer applications.

5.2.5 The APPM domain

The APPM is designed as a collection of interacting autonomous agents, each having its own procedures, plans, and goals. The performance management process that APPM agents are trying to automate is the interaction and negotiation between the various performance elements within a construction project (e.g. cost, schedule, quality, safety, etc.). Each element will enhance its own area of performance and this can lead to conflict as shown earlier. By the process of negotiation and with the help of other agents (e.g. a negotiation and optimization agents), the agents will converge to a solution that leads to overall good results while satisfying certain performance constraints. The following sections will discuss the main components and elements of APPM.

5.2.5.1 A Generic Architecture for APPM

Combining several agents pursuing the same common goal, i.e. overall project performance, leads to the multi-agent project performance management system named (APPM). Figure 5.9 shows a generic architecture for APPM consisting of three major components: users (U), tools (T), and agents (A). The *tools* component includes data and models, which provides information and methods/techniques to the various agents and users. The *agents'* component consists of: (1) a global agent, (2) optimization agent, (3) coordination agent, and (4) local agents. The roles of the various agents and their organizational structure are presented in the following sections.

Because APPM is not completely autonomous, *users* are a major component of the system. Although every agent in the system has enough intelligence to perform independent or cooperative tasks, human supervision is required to: (1) provide input parameters, (2) judge output results, and (3) analyze problems that are beyond the agent's capability.

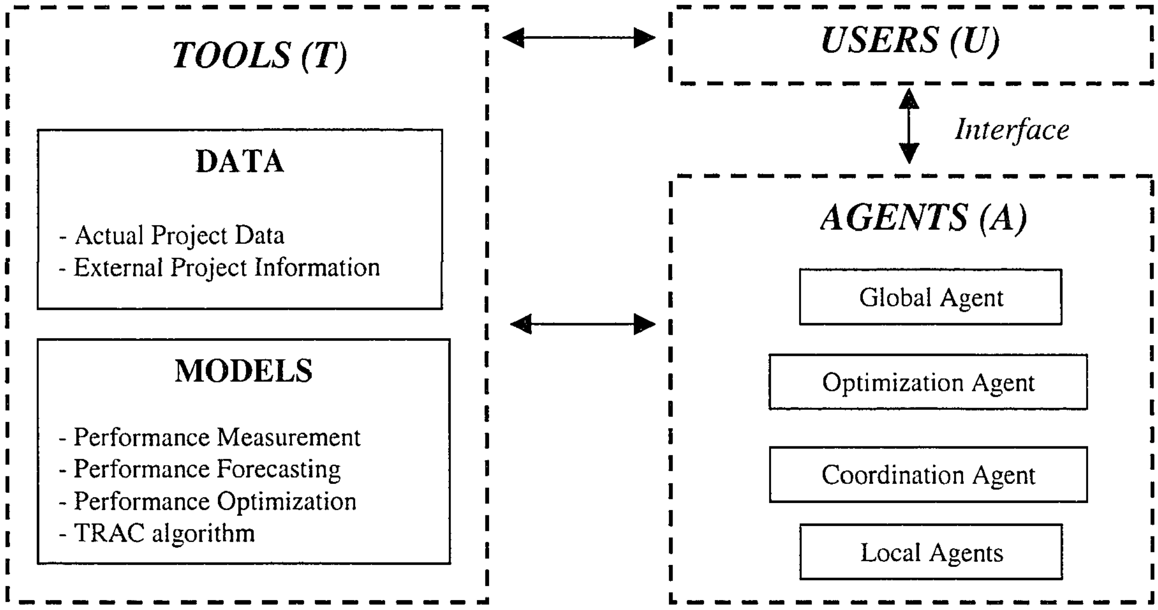


Figure 5. 9 Generic Components of APPM

5.2.5.2 APPM Agents, properties, and structure

Within the context of this study, the word APPM 'agent' denotes a software-based computer implementation that supports a process of autonomous decision-making. Agents are thus autonomous entities that attempt to reach goals by interaction with other agents. An agent can be in dormant, active, or waiting state. The literature is full of many definitions of an intelligent agent and there is no unique definition. However, researchers agree on some generic properties for intelligent agents. According to Wooldridge and Jennings (1995) agents have generally the following characteristics:

- Interactivity: the capability to interact with other agents or human operators.
- Pro-activeness: the ability to take initiatives to satisfy their needs or pre-set goals.
- Reactivity: the ability to perceive changes in its environment and respond in a timely manner.

- Autonomy: the ability to work without the direct intervention of human users and to have direct control over their actions.
- Mobility or social ability: ability to travel within a computer network to gather data and communicate with other agents including humans using some kind of agent-communication language.

The above agent properties are generic and an APPM agent may have more of one property than another based on its architecture and level of intelligence. Also, not all the above properties need to be present in every APPM agent. For example, the *autonomy* characteristic is not fully satisfied by the APPM agent as human decision makers need to intervene and provide directions to the agents at various points.

Structure of an APPM agent

Agents require a structure composed of a set of attributes or elements. In this study, a generic internal structure for each APPM agent is proposed consisting of the following elements as shown in Figure 5.10:

- *Goal*: This is the future performance state that needs to be fulfilled by the agent. *Under budget* cost performance is an example of a goal. Goals help the agent determine what corrective actions or processes to take.

- *State*: An agent can be dormant, or active.

- *Processes*: Each agent has a well-defined set of processes. Each process consists of a set of tasks an agent executes in order to satisfy its desires and achieve its goals.

- *Features*: A feature is a property associated with an agent. In order to achieve their goals, agents carry out actions to satisfy their features.

- *Position*: Each agent has a well-defined position in the agent's organizational structure.

- *Database*: Each agent has an individual information database.

- *Problem solving engine*: Each agent has a set of problem solving techniques and algorithms. Many problems can be solved individually like determination of individual performance areas. Other problems require collaboration among all agents like conflict resolution problems.

- *Address*: Each agent has a name and location.

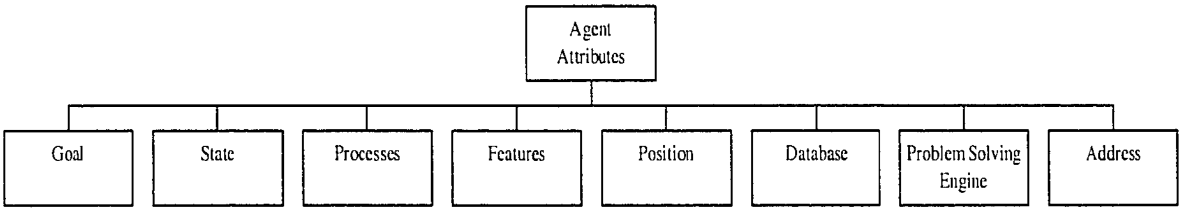


Figure 5. 10 Agent Attributes

5.2.5.3 Types of Agents in APPM

As construction performance optimization is to be carried out by the process of negotiation between agents representing various performance areas within a project, the types of agents must reflect the functionality and capability of each performance area. Moreover, the agents must have basic knowledge about the capabilities of their peers in order to have efficient exchange of information. Based on this, the agent-based integrated performance management system proposed in this research consists of the following agents: Global Agent, Interface Agent, Negotiation Agent, Optimization Agent, and Local Agents (Cost Agent, Schedule Agent, Profitability Agent, Billing Agent, Safety Agent, Quality Agent, Team Agent, and Client Agent). These agents communicate and negotiate to arrive at a better solution. The organizational structure of these agents is described in section 5.2.5.4 and their functionality is described below:

Interface Agent

The *interface agent* is the agent that establishes the necessary interface for the interaction with the human end-users. It allows human operators to visualize data and monitor status of agents with some interactive tools. It also exchanges queries between the human user and the global agent and allows the user to interact with the problem-solving process and to carry out what-if scenarios. This agent compiles the data from the global agent and displays it to the user. Also the interface agent accepts input from the user in form of constraints and provides output in the form of proposed corrective action plans.

Global Agent

The *global agent* is the manager agent that stores a record of all types of agents and handles the coordination, communication, and exchange of messages among all agents. This agent plays a significant role in monitoring and controlling the behavior of agents. It receives the input from local agents and transfers to the negotiation and optimization agents. The job of this agent is also to collect viable and promising corrective action plans from the optimization agent and communicate them to the user through the *interface agent*. To monitor the system, the *global* agent displays the list of agents and the associated list of events to human users.

Negotiation Agent

The *negotiation agent* acts as a controller and a mediator among the competing agents. When the *negotiation agent* receives the plans from other agents, it looks for areas of conflict and starts the negotiation process. These negotiations could be both external (with the user), and internal (with other agents) and aim at removing the performance conflict. This agent uses the TRAC methodology database or the company accumulated experience in order to find a solution that minimizes conflict and then gives it back to the local agents. The *negotiation agent* can communicate directly with the *local agents* to check whether the conflict resolution is satisfactory to them. When the *negotiation agent* arrives to some viable plans it interacts with the *global agent* who in turn feeds the *optimization agent* with the viable options. This agent is only active in the conflict resolution mode.

Optimization Agent

The optimization agent evaluates the viable corrective action options received from the global agent. The optimization technique is based on the project performance optimization function, and using the GA optimization model presented in Chapter 4. The goal of the optimization agent is to propose a set of potential plans that meet the requirements of all local agents (i.e. cost agent, schedule agent, etc.) and satisfy the manager agent.

Local Agents

The local agents are the lowest level agents and model the eight performance elements of a construction project. Each local agent has sub-agents, which model the various sub-objectives. For example, the project schedule agent has three sub-agents: engineering, procurement, and construction. These agents communicate among each other and with the *negotiation agent* to sort out conflicts and find solutions. The local agent also calculates and forecast performance and communicates the results to the *global agent.* The local agents and its sub-agents perform a schedule of tasks as outlined in the developed models. Every local agent, as per APPM, has a precisely specified functionality and uses a specific computer program and set of procedures. As a result, the information is not stored in the *global agent* but kept highly distributed across the community of agents.

An APPM agent will at least need to carry out the following: (1) to represent some external knowledge about the project, (2) to carry-out local problem solving like performance measurement and forecasting, (3) to perform local corrective action, and (4) to exchange information with other local agents, the global and negotiation agents. It should be noted that local agents do not have access to all global information. In fact, the data communication requirements are reduced because agents perform partial processing of local data and communicate only the results. For example, the safety agent will compute the safety performance index (SFI) and will exchange only the outcome to other agents as needed.

5.2.5.4 Agents Organizational Structure

The APPM system contains several agents and needs to be organized. Moreover, the agent-based system attains its goals through interaction between agents and consequently it is very important to adopt an agent-based architecture that facilitates interaction between agents. The organizational structure of agents is one major factor that affects the interaction between agents. Also, the project goals structure affects the agents' organizational structure. In other words, the organizational structure of the respective MAS shall mirror the project goals breakdown structure. The selection of structure will significantly impact the way agents communicate, collaborate, and negotiate. Although the literature includes a wide range of agent structures, most structures are horizontal, vertical, or other variant structures (Lee and Hwang 2004). Every structure includes multiple agents and each agent represents an element of a system and must have at least one goal or objective. For example, the project cost objective is assigned to an agent. An agent in horizontal structure directly communicates with other agents without a mediator. Moreover, there is no central control and each agent needs to have information about other agents. On the other hand, the major disadvantage of vertical layered or hierarchical structures is the challenge to keep all agents well informed which necessitates continuous exchange of large amounts of data.

There would be a major advantage in implementing a hybrid architecture rising from the need for a hierarchical organizational structure to support the vertical project goal structure and need for horizontal communication to support lateral exchange of information and assisted negotiation. As a result, this research adopts a semi-vertical or hybrid agents' structure to support both requirements. Every project objective is assigned to an agent and all agents share the same explicit master or global goal, which is project performance in this case as defined in the IPPM model. This structure has one agent with a *global* vision of the whole process and is identical to a tree structure where the *Global Agent* maintains data about all *Local Agents.* The global agent also exchanges information with the user through the *Interface Agent* as well as with the *optimization agent.* It is not a strictly vertical structure because the *negotiation agent* can communicate with the *local agents* without going through the *Global agent.* This modification is due to the fact that it is very difficult for the *local agents* with different goals to resolve conflicts by all going through the *global agent* thus leading to an information bottleneck.

Figure 5.11 displays the proposed agents' organizational structure. The proposed structure mimics the real world project breakdown structure and the organization of the agents is an approximate mapping of the performance management organization and the integrated project performance management methodology.

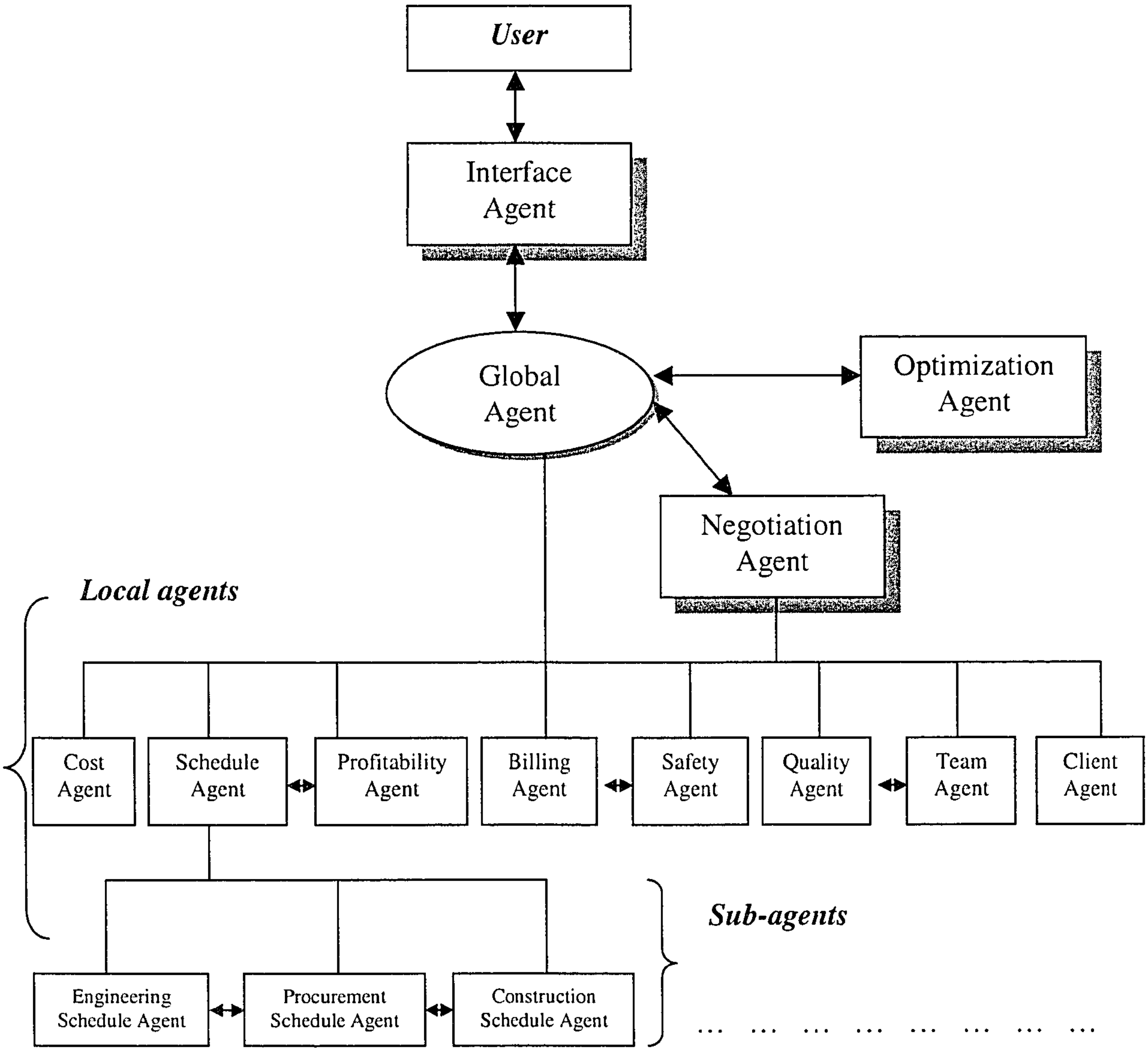


Figure 5. 11 APPM Hybrid agents' organizational structure

5.2.5.5 Negotiation Methodologies in APPM

Cooperation between agents is a key concept, which differentiates MAS from other systems such as expert systems, and distributed object oriented systems. This collaboration is essential for agents to achieve their individual and global goal. However, cooperation between agents and information exchange often leads to disagreements and conflicts. Problems arise when agents communicate to solve a performance problem because the background of each agent differs from the other agents. Each local agent views project performance from its own perspective and lack the global view. When working to achieve a global goal, each agent would like its priorities to be considered first. Unfortunately, the local agent priorities will not be compatible with the global agent priorities thus leading to conflicts. Conflict resolution takes place either through direct negotiation between the agents or through a third party that acts as a mediator or negotiator. In this case, facilitated negotiation is required to resolve conflicts and reach agreement between the local agents. Designing a negotiation mechanism is thus a central issue in MAS.

As highlighted in the first part of this chapter, project objectives are subjected to conflicting interactions. Each agent tries to achieve its own interest without accounting for the overall project interest thus leading to conflicts. As a result, there is a need to coordinate the action of agents to remove conflict and achieve better project performance outcomes. To accomplish this, a negotiation strategy within APPM needs to be implemented. Negotiation can be defined as a process of achieving a point of agreement in an eight dimensional space, where each dimension represents one project performance attribute. Because all agents have conflict of interest, negotiation is needed to satisfy the individual needs of each agent while enhancing at the same time the overall project performance. There are many negotiation methodologies like the negotiation theory, game theory, and the behavior theory that can be used as a basis for an agent negotiation protocol and strategy. But this study uses a negotiation strategy based on the TRAC algorithm for conflict resolution.

The collaborative negotiation methodology using TRAC is most appropriate in APPM because it is aimed at handling conflict situations in which the complexity of the conflict requires a third party. The negotiation agent represents this third party and it plays a mediation role to propose courses of action based on TRAC to resolve contradictions. However, the comprehensive design of an agent negotiation protocol is beyond the scope of this thesis and is part of a future research to develop a functional APPM prototype.

5.2.5.6 Project Goal Breakdown Structure

Performance modeling has become an important aspect in project management in general and project controls in specific. To carry out this task the model must consider all aspects of project performance by dividing the overall project performance into atomic performance indices as discussed in Chapter 2 of this thesis. Based on the project performance breakdown structure proposed earlier, a Project Goal Breakdown Structure is proposed in Figure 5.12, where every performance index /sub-index becomes a goal/sub-goal. This structure will organize the work of the agents whose target is to satisfy the goals they are assigned to. Agents will react based on the status of its sub-goals at a specific time *t*. For example, at time t_n an agent may work with its sub-agent A to achieve sub-goal A, but at time t_{n+1} the same agent may work with sub-agent B to achieve sub-goal B. Therefore, it is of utmost importance to assign agents a set of goals and prioritize those goals.

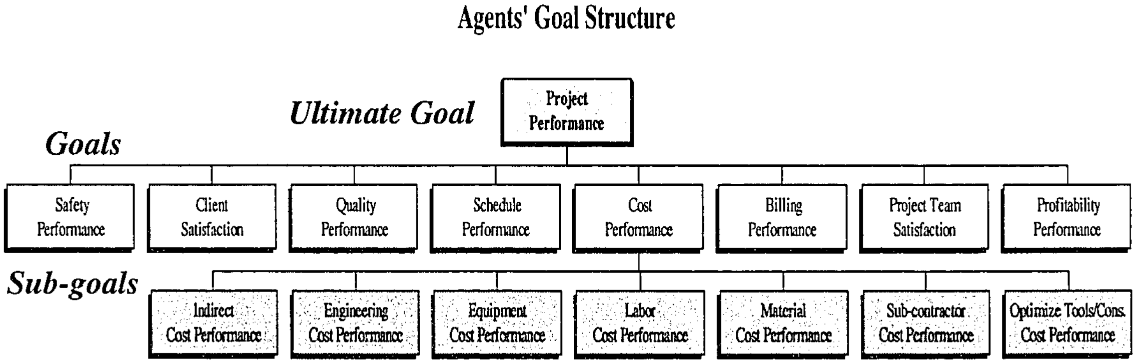


Figure 5. 12 Partial Agents' Goal Structure

5.2.5.7 Goals and Processes

As mentioned above, the organizational structure of the proposed multi-agent system (APPM) shall be identical to the project goals breakdown structure established in Chapter

2. Goals can be classified in a hierarchical structure based on the project objectives' hierarchy, branching down into *goals* and *sub-goals* from one *global goal*. Now define the overall project performance as the "global goal", expressed as ***U***. The performance indices at level 2 and 3 as "goals" and "sub-goals", expressed as ***G*** and ***S*** respectively. We can then write:

$\{G_1, G_2, G_3, G_4, G_5, G_6, G_7, G_8\} \subseteq \{U\}$

And

$\{S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}\} \subseteq \{G_1\}$

$\{S_{21}, S_{22}, S_{23}\} \subseteq \{G_2\}$

$\{S_{31}, S_{32}, S_{33}\} \subseteq \{G_3\}$

$\{S_{41}, S_{42}, S_{43}, S_{44}\} \subseteq \{G_4\}$

$\{S_{51}\} \subseteq \{G_5\}$

$\{S_{61}\} \subseteq \{G_6\}$

$\{S_{71}, S_{72}, S_{73}, S_{74}, S_{75}, S_{76}, S_{77}, S_{78}, S_{79}, S_{710}, S_{711}, S_{712}\} \subseteq \{G_7\}$

$\{S_{81}, S_{82}, S_{83}, S_{84}, S_{85}, S_{86}, S_{87}, S_{88}, S_{89}, S_{810}, S_{811}, S_{812}\} \subseteq \{G_8\}$

Where:

***G_1* = Cost Performance Index (CPI):**

- S_{11} = Indirect Cost Performance Index
- S_{12} = Engineering Cost Performance Index
- S_{13} = Labor Cost Performance Index
- S_{14} = Material Cost Performance Index
- S_{15} = Construction Equipment Cost Performance Index
- S_{16} = Subcontractor Cost Performance Index
- S_{17} = Tools/consumables Cost Performance Index

***G_2* = Schedule Performance Index (SPI):**

- S_{21} = Engineering Schedule Performance Index
- S_{22} = Procurement Schedule Performance Index
- S_{23} = Construction Schedule Performance Index

G_3 = Billing Performance Index (BPI):

- S_{31} = Building Works Billing Performance Index
- S_{32} = Site Works Billing Performance Index
- S_{33} = Off-site Fabrication Billing Performance Index

G_4 = Profitability Performance Index (PPI):

- S_{41} = Civil Works Profitability Performance Index
- S_{42} = Concrete Works Profitability Performance Index
- S_{43} = Mechanical Works Profitability Performance Index
- S_{44} = Electrical Works Profitability Performance Index

G_5 = Safety Performance Index (SFI):

- S_{51} = Lost Time Incident (LTI) Frequency Rate

G_6 = Quality Performance Index (QPI):

- S_{61} = Construction Field Rework Index (CFRI)

G_7 = Team Satisfaction Index (TSI):

- S_{71} = Involvement in the project
- S_{72} = Client/suppliers response to TM needs
- S_{73} = Project Manager response to TM needs
- S_{74} = Adequacy of equipment to get the work done
- S_{75} = Training received to carry out the job
- S_{76} = Financial compensation
- S_{77} = Clarity of project related responsibilities
- S_{78} = Quality of supervision

- S_{79} = Interest in nature of work
- S_{710} = Coordination with the various disciplines
- S_{711} = Execution of work as per Company procedure
- S_{712} = Access to Project Baselines & progress report

G_8 = Client Satisfaction Index (CSI):

- S_{81} = Understanding of the project requirements
- S_{82} = Understanding of Client system & procedures
- S_{83} = Response to the Client requests and/or needs
- S_{84} = Flexibility and adjustment to changes
- S_{85} = Overall capability of contractor project team
- S_{86} = Effective communication
- S_{87} = Innovation in problem solving
- S_{88} = Performance with respect to cost
- S_{89} = Performance with respect to schedule
- S_{810} = Performance with respect to service quality
- S_{811} = Performance with respect to product quality
- S_{812} = Performance with respect to safety procedures

To satisfy the global goal $\boldsymbol{U}$, all the goals $\boldsymbol{G_m}$ and consequently the sub-goals $\boldsymbol{S_n}$ should be achieved. A sub-goal can be achieved by implementing one or many corrective actions or processes $\boldsymbol{P_r}$. When a threshold value for a sub-goal or performance index is reached, the responsible agent is activated and as a result one or many associated processes are triggered. Note that a Process $\boldsymbol{P}$ is a set of tasks $\boldsymbol{T}$ utilizing resources $\boldsymbol{R}$ to achieve a sub-goal S. The relationships between goals, processes, tasks, and resources are schematically shown in Figure 5.13.

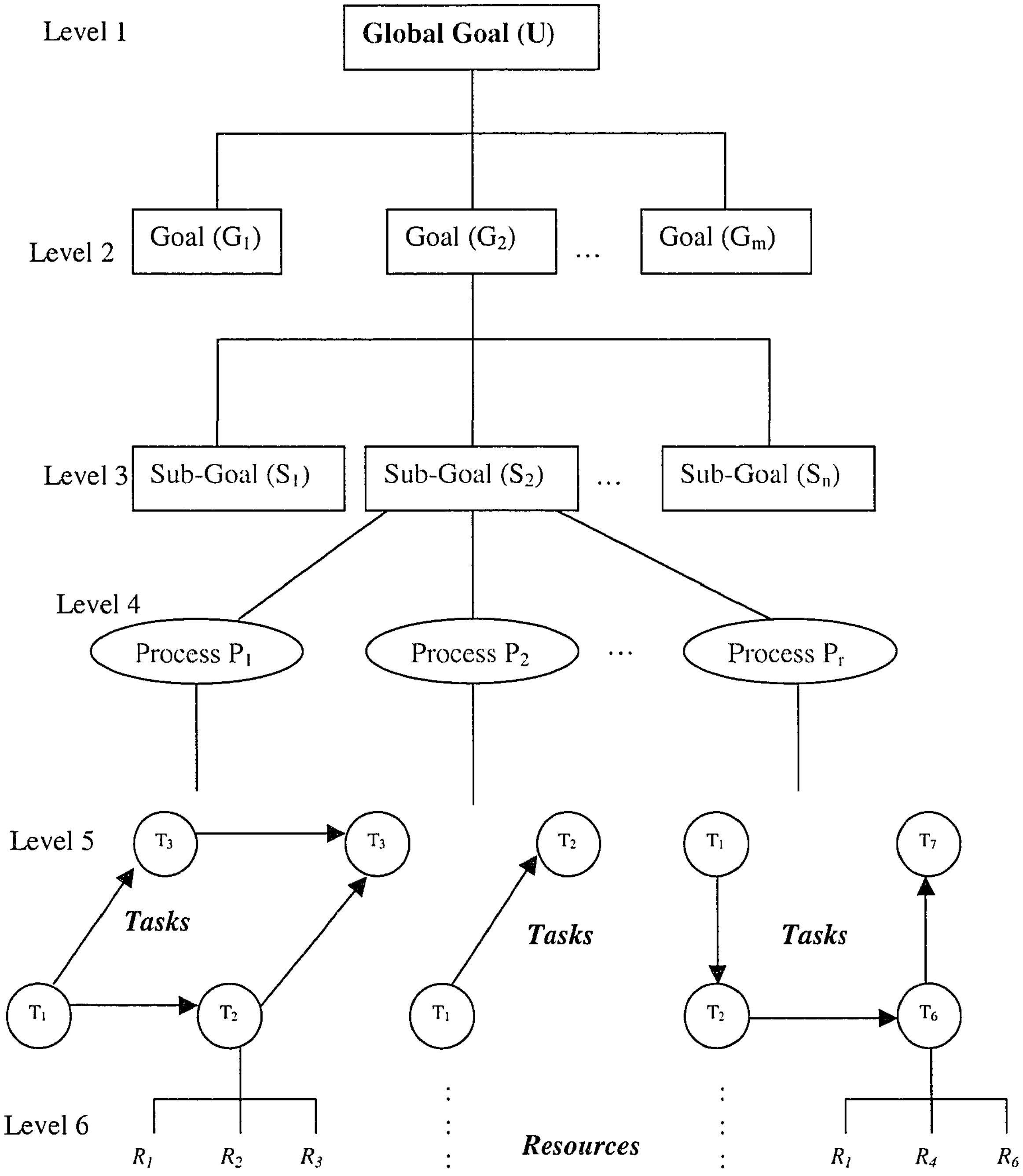


Figure 5. 13 Typical Goal Hierarchy showing: processes, tasks and resources

With reference to the above figure, at least one of the "*r*" processes ($P_1, P_2, \ldots, P_r$) must be implemented to achieve sub-goal S_2. In other words, when one or more than one process is executed successfully, the sub-goal S_2 is satisfied. Processes can have common tasks that utilize common resources, for example, tasks T_1 and T_2 are common for processes $\boldsymbol{P_1}$, $\boldsymbol{P_2}$, *and* $\boldsymbol{P_r}$.

Thus we can write:
Satisfied (S_2) = Completed ($\boldsymbol{P_1}$) and/or Completed ($\boldsymbol{P_2}$) and/or.....And/or Completed ($\boldsymbol{P_r}$)

$$S_2 = P_1 \cup P_2 \cup .... \cup P_r \qquad \text{Equation (5.1)}$$

Using the same approach, a goal can be defined in terms of its sub-goals as:

$$G_2 = S_1 \cup S_2 \cup .... \cup S_n \qquad \text{Equation (5.2)}$$

And the global goal is defined in terms of its goals as:

$$U = G_1 \cup G_2 \cup .... \cup G_m \qquad \text{Equation (5.3)}$$

It should be noted that the intersections between the Processes $\boldsymbol{P_1}$, $\boldsymbol{P_2}$, *and* $\boldsymbol{P_r}$ are not necessarily void, or mathematically speaking $P_1 \cap P_2 \cap P_3 \neq \{\phi\}$ as the case is in Figure 5.13, where $\mathrm{P_1 \cap P_2 \cap P_r = \{T_1, T_2\}}$. Moreover, one resource can serve more than one task.

5.2.5.8 Activation of Agents and Prioritization of Goals

As shown above, an agent could manage one or a set of goals. For example, the Project Cost Agent is responsible for managing the cost performance goal (G_1) that is composed of many sub-goals, namely$\{S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}\}$. The agent in this case has seven sub-goals that it may execute to satisfy the cost goal. Each of these goals and subsequently each sub-goal have a certain level of priority. The level of priority indicates how urgent or significant the agent is to implement certain processes to fulfill that goal. For each sub-goal there is a set of processes that the agent may select to achieve its goal. When a threshold value (T_V) of a certain goal is reached, adequate actions are triggered in the agent.

Construction projects have a complex goal hierarchy as shown above in Figure 5.13, and it is desired to achieve all goals simultaneously but this is not feasible due to resources and time constraints encountered by all projects. This will lead to *goal prioritization* and to the definition and measurement of *goal urges*. It should be noted at this point that the level of the goal in the hierarchy is independent of the priority placed on that goal. The intensity of an urge and the motivation to satisfy the associated goal are directly proportional, the higher the urge is the higher the motivation to satisfy the goal. Intensity of urges should be measured since it impacts how and when agents are triggered to satisfy a set of goals. The urge that triggers the agent's activity is also a function of the outcome of the processes that are used to satisfy the agent's goal.

For example, assume the *labor cost performance goal* (S_{13}), at the end of a certain reporting period, has a positive urge intensity value I. The agent will then work to satisfy its goal with the appropriate process. The agent, after successfully completing the process, will have partially or fully satisfied *sub-goal* (S_{13}) and the agent's urge intensity will have been lowered with a new value $I' < I$. In most cases, the execution of one process may not completely diminish the urge intensity of the goal, that is $I'=0$, and the agent may want to implement other processes. Moreover, the outcome of the agent work may not be realized in the next reporting period and most probably will take few periods before the urge intensity is decreased or diminished. This is due to the fact that most corrective action plans need time for execution and the expected results will be realized at a later time. The goal satisfaction process is shown in Figure 5.14.

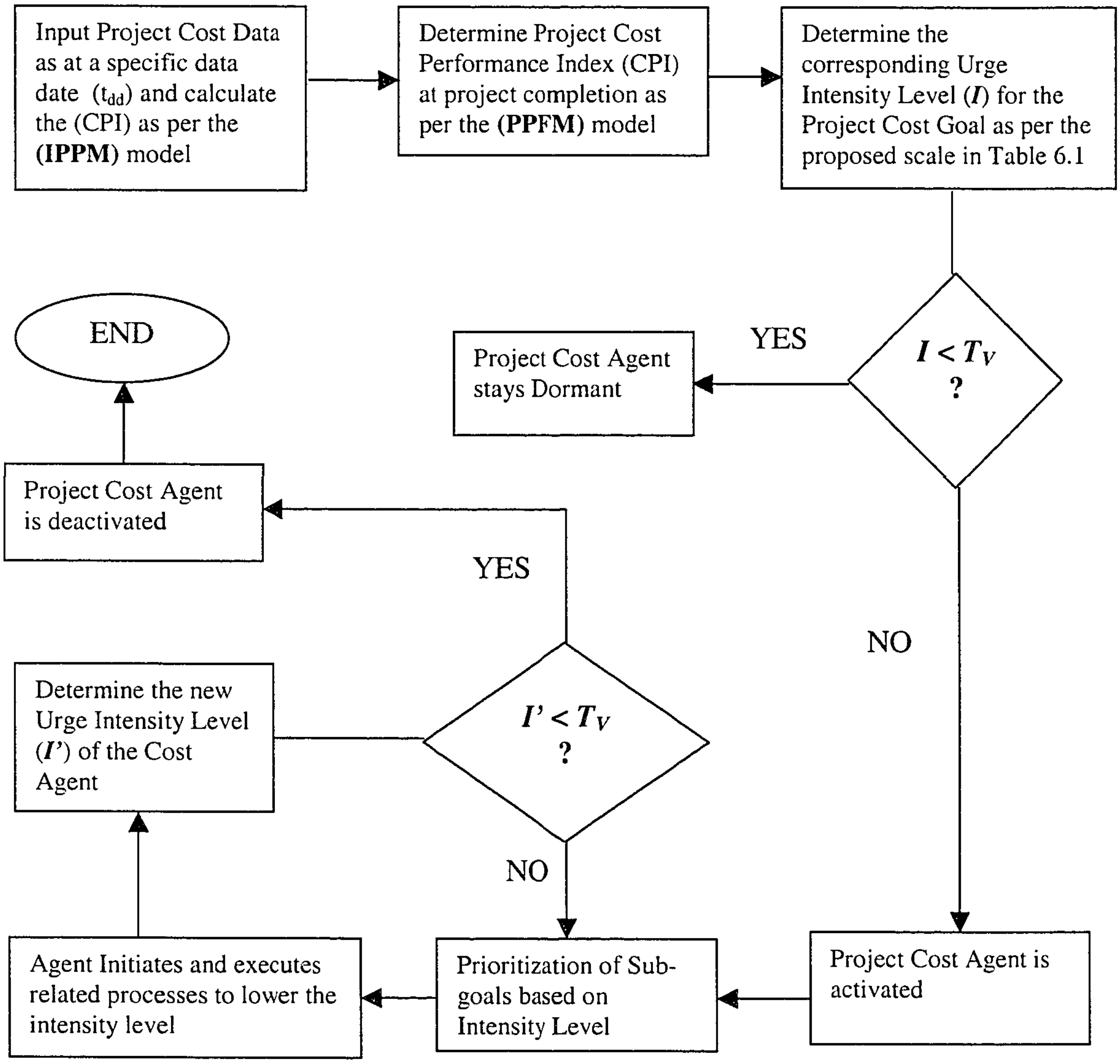


Figure 5. 14 Corrective Action Process Flow Chart for the Project Cost Agent

In other words, we can define a set of urge intensities I for any sub-goal/goal where $I = \{I_1, I_2 ..., I_n\}$. The urge intensity of an agent (A) at any future point in time $(t + \Delta t)$ can be defined as:

$$I_A(t + \Delta t) = I_A(t) + G_A(t, t + \Delta t) - S_A(t, t + \Delta t) \qquad \text{Equation (5.4)}$$

Where:

I = Urge Intensity of Agent A, is proportional to the total intensity of the urges of all the sub-goals managed by Agent A.

G = Change (Increase/decrease) in Urge Intensity of Agent A since time t.

S = Amount of satisfaction received by Agent A since time t.

Equation (5.4) shows that the intensity of an urge for an *agent A* is equal to the previous intensity value plus any change in the intensity minus any satisfaction of that intensity due to meeting the goal outcomes. The urge intensity of *agent A* is satisfied when:

$$S_A(t+\Delta t) = I_A(t) + G_A(t, t+\Delta t) \qquad \text{Equation (5.5)}$$

Urge/sub-urge intensities measure the degree of motivation to satisfy a certain goal/sub-goal where motivation is inversely proportional to the performance condition of each goal. The lower the performance is, the higher the urge value, and the higher is the motivation to satisfy the goal. Based on above, a scale of urge intensities is proposed in Table 5.9 to prioritize goals. The proposed scale has to be modified for every project.

Table 5. 9 Proposed Scale of Urge Intensities

Condition	**Rating**	**State**	**Index Range**	**Intensity (I)**
A	Outstanding Performance	A1	I > 1.25	1
		A2	1.15<I<= 1.25	2
B	Exceeds Target	B1	1.10<I<= 1.15	3
		B2	1.05<I<= 1.10	4
C	Within Target	C1	1.00<I<= 1.05	5
		C2	0.95<I<= 1.00	6
D	Below Target	D1	0.90<I<= 0.95	7
		D2	0.85<I<= 0.90	8
F	Poor Performance	F1	0.75<I<= 0.85	9
		F2	I<= 0.75	10

Not all agents responsible for corrective action are always active. Agents are activated to act and achieve their goals only when the urge intensity level (I) reaches the *threshold value* (T_V). At this point, the agent is triggered to start a set of processes to satisfy its sub-goals. Threshold values (T_V's), assigned by the project management team, should be defined for all goals in the hierarchy.

5.2.5.9 Agent's Operation Zone

The main function of a local agent and its sub-agents is to implement processes to enhance project performance and make the Actual Project Performance (APP) as close as possible to the Target Project Performance (TPP). While traveling from (APP) to (TPP) in search for a solution, it is not necessary to work outside the boundaries of the operation zone as shown in Figure 5.15. Confining the search within the system boundaries will make the solving process clearer, practical and permits the agent to arrive at a potential or highly probable solution in an efficient manner. It should be noted that timely corrective action is vital to the success of projects.

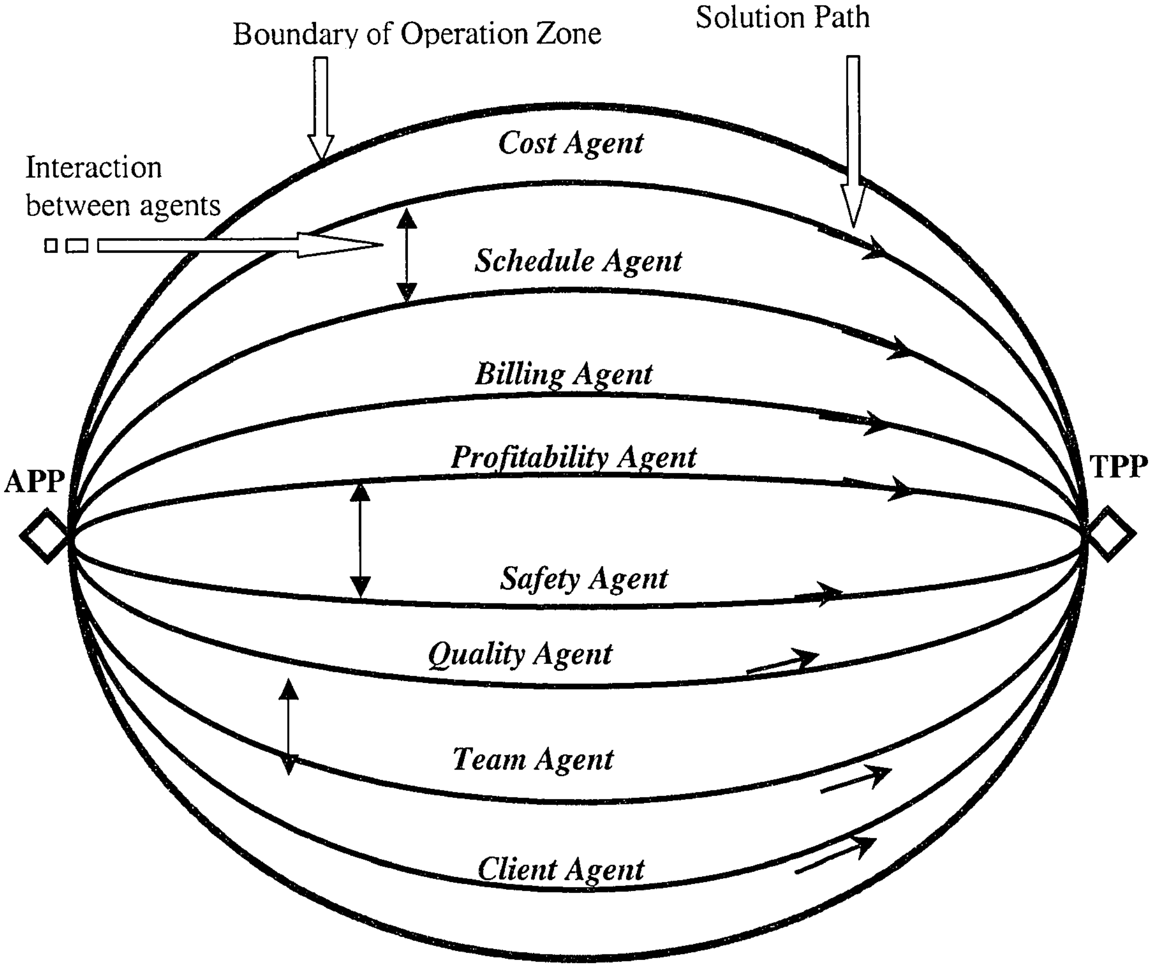


Figure 5. 15 Agents' Operation Zone

5.2.5.10 Agents' Action Tree

Each agent has properties that need to be satisfied through actions. Actions are carried out through execution of processes that are made up of tasks. Processes, as a network of tasks, should achieve the desired agent's properties. Figure 5.16 displays a partial Agents' Action Tree that organizes the work of the agents and directs their action to enhance the overall project performance.

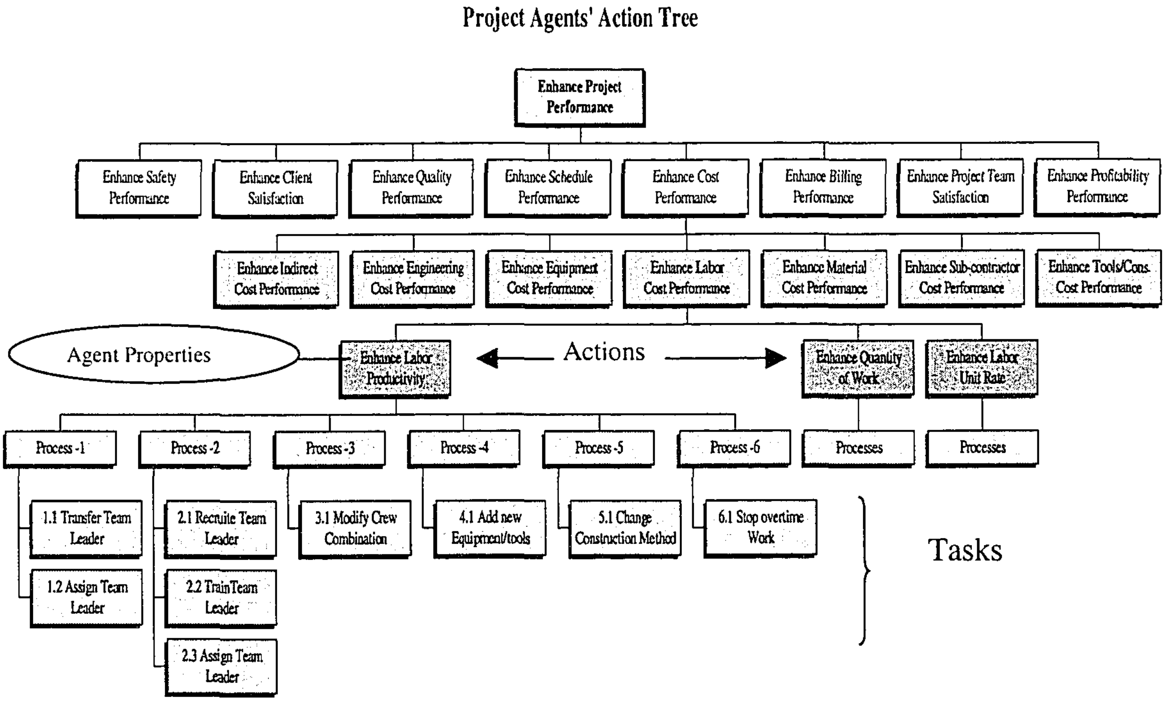


Figure 5. 16 Partial Project Agent's Action Tree

5.2.5.11 Agent's Features

In order to achieve their goals, sub-agents carry out actions to satisfy their features. A feature is a property associated with an agent where each agent has its own features. A specific feature could exist in more than one agent as illustrated in Figure 5.17 where the "*No Overtime Work*" feature is shown under both agents.

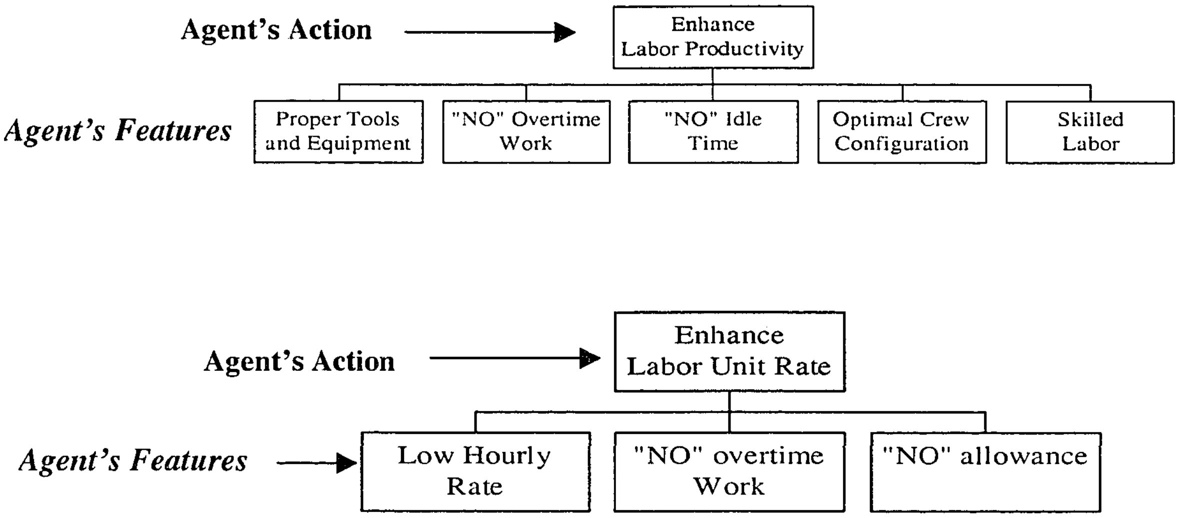


Figure 5. 17 Features associated with the labor cost sub-agents

It should be noted that features can be conflicting, for example the "*skilled labor*" feature of the *Labor Productivity sub-agent* may contradict with the "*low hourly rate*" feature of the *Labor Unit Rate sub-agent.* In other words, recruitment of "*skilled labor*" increases the *labor productivity* performance but may increase the "*hourly rate*" thus decreasing the *labor unit rate* performance. On the other hand, the "*No Overtime Work*" feature listed under both agents list of actions can be a strong solution candidate. Conflicts among features are resolved via communications among agents assisted by the *negotiation agent*, which can use TRAC algorithm for conflict resolution.

5.2.6 Future Research

The proposed framework will pave the road to the next stage of research which includes the development of an agent-based functional prototype system where users and their software tools are federated using an agent communications language (ACL). The prototype can be used to test and verify the proposed framework and ultimately facilitate the construction of an agent-based simulation model. The prototype needs to be validated by construction companies in terms of reliability, efficiency, and applicability to actual projects.

5.2.7 Conclusion

The construction industry today is facing increasing dynamic and project performance complexity. In order to overcome the drawbacks of a centralized knowledge-based system and maintain a competitive edge in the market, construction organizations need to use distributed intelligent systems like multi-agent systems to support the decision making process and make it more efficient and effective. To our knowledge, agent technology has never been applied to integrated performance management of construction projects.

This study recommends the application of multi-agent systems as a substitute for large monolithic systems. This is due to the fact that the whole performance control cycle as mandated by the IPPM model involves the use of many software tools that cannot automatically cooperate. In order to reduce the computational overhead of transferring output of one tool to the input of another, and in order to avoid mistakes in data entry; the control cycle is modeled by a network of cooperating agents named APPM.

The main concern of this chapter is the development of a high-level MAS architecture for project performance in which agents, representing the eight performance aspects, can carry out assisted negotiation with each other to resolve construction performance conflicts. The contributions to the users, i.e., the project team members, will be better ways to deal with conflict among the competing performance objectives.

The distributed approach proposed will allow individual aspects of project performance to be encoded into intelligent agents, thus modeling the problem of performance. This research introduced a framework for managing a distributed project performance system using agents. It shows how the various performance indices can be distributed but coordinated by using multi-agents. One conclusion can be drawn from this study and that MAS's have great potential to improve the efficiency of the performance management process (measurement, forecasting, and optimization) presented earlier in this thesis.

REFERENCES

Altshuller, G., (2000). *The Innovation Algorithm: TRIZ, Systematic Innovation, and Technical Creativity*, translated by L. Shulyak and S. Rodman, Technical Innovation Center, Worcester, MA.

Altshuller, G., (1998). *40 Principles: TRIZ Keys to Technical Innovation*, translated by L. Shulyak and S. Rodman, Technical Innovation Center, Worcester, MA.

Anumba, C. J., Ugwu, O. O., Newnham, L., and Thorpe, A., (2002). "Collaborative design of structures using intelligent agents." *Automation in Construction*, 11(1), 89-103.

Anumba, C. J., Ren, Z., Thorpe, A., Ugwu, O. O., and Newnham, L., (2003). "Negotiation within a multi-agent system for the collaborative design of light industrial buildings." *Advances in Engineering Software*, 34(7), 389-401.

Aylett, R., Brazier, F., Jennings, N., Luck, M., Nwana, H., and Preist, C. (1997). "Agent systems and applications." *Second UK workshop on foundations of multi-agent applications (FoMAS).*

Burmeister, B., Haddadi, A., Matylis, G., (1997). "Application of multi-agent systems in traffic and transportation." *IEE Proc. Software Engineering*, 144 (1), 51-60.

Chang Hsiang-Tang, and Chen, Jahau Lewis, (2004). "The conflict-problem-solving CAD software integrating TRIZ into eco-innovation." *Advances in Engineering Software*, 35(8-9), 553-566.

Domb, Ellen, (2000). "Managing Creativity for Project Success." *Proceedings of the 7th Project Leadership Conference*, June 2000.

Dull, C. Bernerd, (1999). "Comparing and Combining Value Engineering and TRIZ Techniques." *Proceedings of the SAVE International Conference*, 34, 71-76.

Dzeng, Ren-Jye, and Lin, Yu-Chun, (2004). "Intelligent agents for supporting construction procurement negotiation." *Expert Systems with Applications*, 27(1), 107-119.

Ferber, J., (1999). *An Introduction to Distributed Artificial Intelligence*, Addison-Wesley, New York.

Fey, V., and Rivin, E., (1997). *The Science of Innovation: A Managerial Overview of the TRIZ Methodology*, The TRIZ Group, Southfield, MI.

Kim, Sung-Keun, and Russell, Jeffrey S., (2003). "Framework for an intelligent earthwork system: Part I. System architecture." *Automation in Construction*, 12(1), 1-13.

Kim, Keesoo, and Paulson, Boyd C. Jr., (2003). "Agent-Based Compensatory Negotiation Methodology to Facilitate Distributed Coordination of Project Schedule Changes." *Journal of Computing in Civil Engineering*, 17(1), 10-18.

Kourmaev, Roustem, and Teplitskiy, Abram, (2003). "Application of Inventing Problem-Solving Theory (TRIZ) in Pipeline Technologies." *ASCE Pipelines Proceedings 2003*, 1465-1471.

Lee, S. K., and Hwang, C. S., (2004). "Architecture modeling and evaluation for design of agent-based system." *The Journal of Systems and Software*, 72(2), 195-208.

Lees, Brian, Branki, Cherif, and Aird, Iain, (2001). "A framework for distributed agent-based engineering design support." *Automation in Construction*, 10(5), 631-637.

Mann, Darrell, and Cathain, Conall O., (2001). "40 Inventive (Architecture) Principles with Examples." *The TRIZ Journal*, July 2001.

Mann, Darrell, and Domb, Ellen, (1999). "40 Inventive (Business) Principles with Examples." *The TRIZ Journal*, Sep. 1999.

Marsh, Dana G., Waters, Faith H., and Marsh, Tabor D., (2004). "40 Inventive Principles with Applications in Education." *The TRIZ Journal*, April 2004.

Mohamed, Y., (2002). *A framework for systematic improvement of construction systems,* PhD thesis, University of Alberta, Edmonton, AB.

O'Hare, G.M.P., Jennings, N.R, (1996). *Foundations of Distributed Artificial Intelligence*, Wiley, New York.

Petrie, Charles, Goldmann, Sigrid, and Raquet, Andreas, (1999). "Agent-Based Project Management." *IJCAI- 1999 Workshop on workflow and Process Management*, 1-2 August, Stockholm, Sweden.

Rantanen, K., and Domb, E., (2002). *Simplified TRIZ: new problem-solving applications for engineers & manufacturing professionals*, CRC press, Boca Raton, Florida.

Ren, Z., Anumba, C. J., and Ugwu, O.O., (2003). "The development of a multi-agent system for construction claims negotiation." *Advances in Engineering Software*, 34(11-12), 683-696.

Retseptor, Gennady, (2003). "40 Inventive Principles in Quality Management." *The TRIZ Journal*, March 2003.

Royzen, Zinovy, (1993). “Application TRIZ in Value Management and Quality Improvement.” *Proceedings of the International Conference of the Society of American Value Engineers (SAVE)*, Fort Lauderdale, Florida, May 1993, 28, pp. 94-101.

Savransky, S. D., (2000). *Engineering of creativity: Introduction to TRIZ methodology of inventive problem solving*, CRC press, New York.

Shtub, Avraham, (1995). “Distributed database for project control.” *International Journal of Project Management*, 13(3), 173-176.

Smith, S., (1992). “Towards an intelligent planning system.” *International Journal of Project Management*, 10(4), 213-218.

Stratton, R., and Mann, D., (2003). “Systematic innovation and the underlying principles behind TRIZ and TOC.” *Journal of Materials Processing Technology*, 139(1-3), 120-126.

Stratton, R., and Warburton, R. D. H., (2003). “The strategic integration of agile and lean supply.” *International Journal of Production Economics*, 85(2), 183-198.

Terninko, John, (2001). “40 Inventive Principles with Social Examples.” *The TRIZ Journal*, June 2001.

Wooldridge, M., (2002). *An introduction to multiagent systems*, Wiley, New York.

Woolridge, M., Jennings, N.R., (1995). “Intelligent Agents: Theory and Practice.” *The Knowledge Engineering review*, 10(2), 115-152.

Yan, Yuhong, Kuphal, Torsten, and Bode, Jurgen, (2000). “Application of multiagent systems in project management.” *International Journal of Production Economics*, 68(2), 185-197.

Chapter 6

General Discussion and Conclusions

6.1 Discussion

To keep the competitive edge construction organizations have to use an integrated project performance management system across all their projects. Facing reduced profit margins and a competitive market, senior management of construction organizations now realize the importance of project performance evaluation and management. However, they lack the right and effective tools for measuring and forecasting performance and project managers rely heavily on their experience for proposing and implementing corrective action plans. Moreover, the existing systems do not integrate the various phases of performance, which is evaluation, forecasting, and optimization. This research aimed at filling this void by offering an integrated project performance management system for use by the decision-makers in the construction industry. Although the proposed system is based on quantitative models, it does not eliminate the role of sound subjective judgment by users. It helps the project manager to be more effective and efficient in decision-making.

This research proposed innovative tools for use by construction organizations that can provide timely and reliable information that could lead to less variability in terms of cost, schedule, safety, quality, and profitability as well as better management for other intangibles like project team and customer satisfaction. In today's highly competitive environment, monitoring the quantitative goals of a project is not sufficient. Managing the project team as well as the client in an effective way can also have a significant impact on the success of a project and the construction company.

The proposed tools and models will provide the project management team with means to assist in selecting the proper course of action and strategy in order to achieve a good project performance. The proposed system is not intended to replace the project manager but to augment his/her subjective analysis by a set of systematic procedures.

6.1.1 Decision-making and optimality

In discussing optimality in Chapter Five, the best course of action with respect to the decision maker is not necessarily the *computed* optimal one. It is accepted that, given the same decision problem, two project managers might select two different plans of action. This is mainly due to two reasons: (1) the model input parameters and priorities may differ from one user to another thus leading to two different output results, and (2) the user may select a near optimal plan and modifies it to consider non-modeled factors (instead of adopting the model output as is).

In summary, the proposed optimization model is not one of pure rationality and optimality, but it is a practical and effective approach developed to help a competent project manager choose his own decision in a timely and systematic manner.

6.1.2 Performance Management Process– Best Practice

Performance management as outlined in this research could be implemented as a corporate best practice that applies to all projects. To have successful implementation, project participants should be aware of and believe in the following:

- The level of effort expended on setting up the proposed performance management system has a significant impact on project success.
- Performance Management is a process that a company can standardize and implement.
- The three primary sub-processes in performance management are: measurement; forecasting; and analysis/corrective action.
- Performance Management is a contractor-driven process that must reflect the organization business goals.

- This research proposes an integrated performance management process that can assist construction companies achieve project success.
- Performance Management is complex and multi-functional process. Contracting companies must modify some parameters to meet their business needs and objectives.
- The input by the decision maker is critical to the success of the process.
- Decision makers must define the project goals and provide guidelines to benchmark actual performance.
- Teamwork and communication are critical to the Performance Management process.
- To implement the Performance Management Process successfully, companies must allocate adequate resources and time. Qualified and experienced project teams are required to verify inputs to the models, conduct analysis, and make recommendations.
- The project and functional managers within the organization need to understand that they have different views regarding project success and objectives. These managers must communicate their views and agree on project objectives and performance threshold values.

6.2 Research Contributions

The contributions of this thesis are mainly in the development of techniques, or methods, which can help project managers in a construction organization, analyze complex decision problems and recommend plans of action that would achieve the project stated objectives. The major contributions are summarized as follows:

- **Integrated method to measure project performance**: The proposed (IPPM) model is based on a unified project performance breakdown structure and implements a new approach to evaluate the performance of projects in a formal and systematic way.

- **New Performance Forecasting Tool**: The proposed research introduced a new project performance forecasting tool based on *dynamic Markov chains*. The new method will assist the project manager to predict the stochastic behavior of project performance at any future time and carry out sensitivity analysis and what-if scenarios.

- **Performance Optimization Tool using Genetic Algorithms:** Development of an optimization model using genetic algorithms to select highly feasible and effective set of corrective action plans that will lead to better project performance.

  Based on above, the GA model will propose not only the optimal solution but also a set of near optimal solutions. Again, the *computed optimal* solutions offered by the GA model are not necessarily the *best* course of action. This is due to the fact that in construction performance management there are many interdependent internal and external (client related) qualitative factors that are not easy to quantify or model but can have significant impact on the decision taken. A sound plan must be augmented by an expert assessment. The proposed tool will only *assist* the decision-maker select a *better or improved* course of action and is never intended to completely replace human judgment.

- **Performance Conflict Resolution Guide:** This unique tool will assist construction team leaders to develop creativity and innovative thinking. The proposed matrix guides decision makers to minimize or remove conflict among competing project attributes in a timely and effective manner.

- **Agent-based Performance Management Framework:** Today's project controls tools are still based on separate disconnected models for controlling cost, schedule, safety, quality, and profitability. The proposed (APPM) framework establishes an infrastructure to support the distributed task interactions of modern total project controls and to render the practical implementation of the above proposed models by contractors a viable option.

6.3 Research Contributions – An Integrated Model

The above proposed tools and models when combined together will form *An Integrated Framework for Evaluation, Forecasting and Optimization of Performance of Construction Projects* as shown in Figure 6.1.

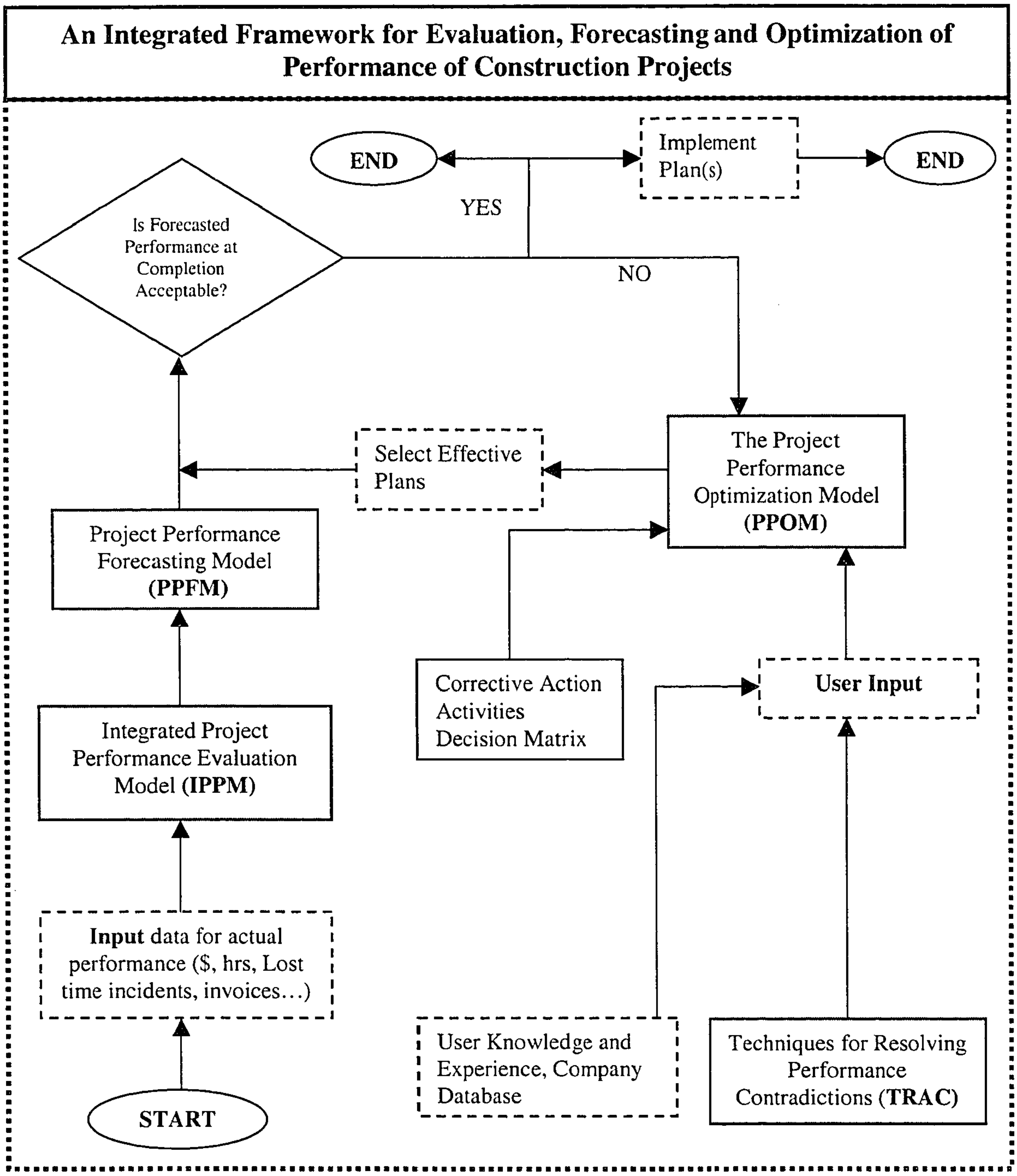


Figure 6. 1 Integrated Research Model

6.4 Research Implementation Requirements

The implementation of the models and methods developed and proposed in this thesis by construction practitioners can face many challenges and barriers some of which are:

- Lack of expertise by the implementing company in one of several areas (technical, managerial, or administrative) stresses the execution process due to the inability of the involved parties to populate the models, communicate, and interpret the results for better decision making. It must be emphasized that valid input by users and correct analysis of output results are vital to successful implementation of the proposed performance management system.

- A poorly defined scope of work hinders the process of defining and prioritizing objectives, and setting up an adequate performance forecasting and optimization models. This leaves the decision makers without any guidance for evaluating the alternative courses of action.

6.5 Recommendations for Future Research

The theoretical foundations of a *performance conflict resolution methodology* and a *distributed performance management system* using agents were established in chapter 5 of this thesis. However, these two vital areas of future research are of great significance to the practitioner and need to be elaborated for potential application in the construction industry. The following two areas are strong candidates for future research:

6.5.1 Construction and validation of the (TRAC) Matrix

Case studies and lessons learned of completed construction projects need to be analyzed in order to complete and validate the proposed project performance resolution techniques. The performance contradiction matrix should solve the majority of existing conflicts and withstand the validation tests under various circumstances and project conditions prior to implementation by the construction industry.

6.5.2 Building an Agent-based Project Performance Management System

This research has demonstrated that integrated performance management requires a new distributed approach whereby all the concerned parties can work together more closely, communicate the project status in a more structured way, and solve performance contradictions in a timely manner. This work initiated the idea of multi-agent systems as a technique to assist users communicate performance, propose alternatives, negotiate, and solve performance conflicts. Future research includes the development of a functional agent-based prototype system where users and their tools, as presented in this research, are federated using an agent communications language (ACL).

6.6 Concluding Remark

At a macroscopic level, we know that budgets are getting tighter and clients more demanding. Therefore, it is essential that construction organizations understand and implement a systematic and effective process for performance management. The objective of the proposed work is to help construction companies manage their projects in a more efficient way that will translate into more business and ultimately more growth and profit.

Appendix (A) - Numerical Illustration

A-1 Objective

The objective of this section is to illustrate the application of the performance evaluation and forecasting models (IPPM and PPFM) through a numerical example.

A-2 Scope

For demonstration purposes, a case study using sample project data was compiled to illustrate the application of the unified measurement and forecasting methodology presented in this research. The sample project is an airport rehabilitation project in Cold Lake, Alberta carried out by a local contracting company. This example will attempt to demonstrate the use of the mathematical concepts and methodology of performance measurement and forecasting and does not reflect any actual project outcomes. The project consisted mainly of earthwork, asphalt, and concrete pavement work. A partial work breakdown structure is shown in Figure A-1.

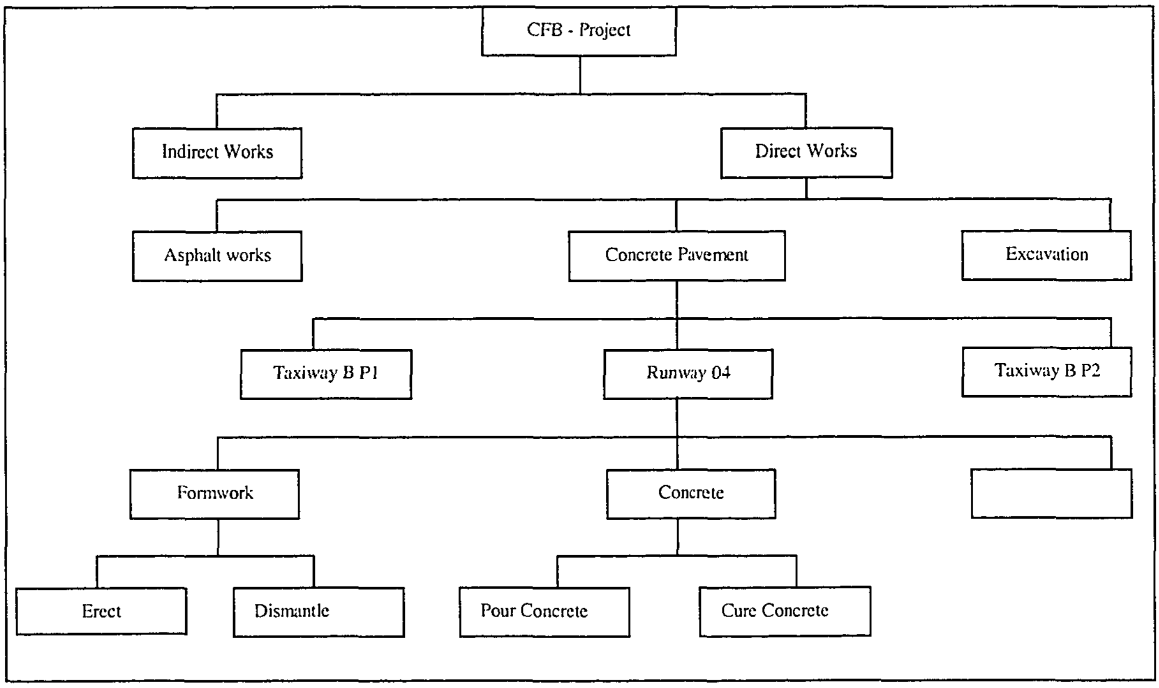


Figure A- 1 Partial Work Breakdown Structure

For the purpose of illustration, the project is divided into 11 work packages as shown in Table A-1. This table displays the estimated cost, budgeted cost, budgeted man-hours, and revenue for each construction work package. It should be emphasized that all data are scaled and shown for demonstration purposes only. Moreover, many data assumptions are made in order to demonstrate the proposed methodology.

Table A- 1 Project Baseline Data

s/n	WP- Code	Work Package	Budgeted Manhours		Budgeted Cost ($)		Revenue ($)	
			Amount	Wt. %	Amount	Wt. %	Amount	Wt. %
1	WP-01	Removal of existing pavement	650	3.80	172,209	5.94	196,157	5.96
2	WP-02	Excavation	562	3.28	74,950	2.59	82,404	2.50
3	WP-03	Subgrade compaction and backfilling	769	4.49	102,515	3.54	154,401	4.69
4	WP-04	Sub-base	1,103	6.44	147,109	5.08	169,151	5.14
5	WP-05	Basecourse	634	3.70	84,532	2.92	97,214	2.95
6	WP-06	Asphalt Pavement	980	5.72	500,937	17.29	664,219	20.18
7	WP-07	Concrete Pavement	6,439	37.61	858,569	29.63	924,019	28.07
8	WP-08	Manholes, gratings and drains	1,752	10.23	233,633	8.06	245,314	7.45
9	WP-09	Fences and gates	184	1.08	24,543	0.85	25,784	0.78
10	WP-10	General Finishing Works	487	2.84	64,916	2.24	68,597	2.08
11	WP-11	Electrical Works	3,560	20.79	633,356	21.86	665,015	20.20
		TOTAL	**17,121**	**100.00**	**2,897,268**	**100.00**	**3,292,277**	**100.00**

A-3 Overall Project Performance Measurement

The following steps are used to calculate the actual cumulative project performance. The project duration is divided into 20 weeks or reporting periods.

Step1: Determine the S-curves by man-hours, cost, and revenue

Using the baseline data shown in Table A-1 and the schedule baseline, a time-based distribution by % of man-hours, cost and revenue are obtained as shown in the following table A-2. The table shows periodic and cumulative data for each of the three project parameters.

Table A- 2 Time-based distribution of baseline data

s/n	Period	Budgeted Manhours		Budgeted Cost ($)		Revenue ($)	
		% this period	% Cumulative	% this period	% Cumulative	% this period	% Cumulative
1	T-01	1.00	1.00	1.50	1.50	1.30	1.30
2	T-02	1.50	2.50	2.00	3.50	1.80	3.10
3	T-03	2.50	5.00	2.50	6.00	2.20	5.30
4	T-04	3.50	8.50	3.00	9.00	3.80	9.10
5	T-05	4.00	12.50	3.80	12.80	4.30	13.40
6	T-06	4.50	17.00	4.20	17.00	5.25	18.65
7	**T-07**	5.43	**22.43**	4.80	**21.80**	5.90	**24.55**
8	T-08	7.00	29.43	6.00	27.80	6.40	30.95
9	T-09	7.50	36.93	6.80	34.60	6.80	37.75
10	T-10	8.00	44.93	7.10	41.70	7.30	45.05
11	T-11	8.00	52.93	7.20	48.90	7.50	52.55
12	T-12	8.00	60.93	8.30	57.20	7.60	60.15
13	T-13	7.57	68.50	8.50	65.70	8.50	68.65
14	T-14	7.50	76.00	7.80	73.50	7.50	76.15
15	T-15	7.00	83.00	7.00	80.50	6.40	82.55
16	T-16	6.50	89.50	6.50	87.00	6.20	88.75
17	T-17	4.00	93.50	5.20	92.20	4.70	93.45
18	T-18	2.50	96.00	3.50	95.70	3.10	96.55
19	T-19	2.50	98.50	3.00	98.70	2.50	99.05
20	T-20	1.50	100.00	1.30	100.00	0.95	100.00
		100		**100**		**100**	

Based on the above table, the associated S-curves are constructed as shown below.

1. Project S-curve by Man-hours

Using the man-hours budget and the schedule baseline, the man-hours S-Curve is obtained as shown below in Figure A-2.

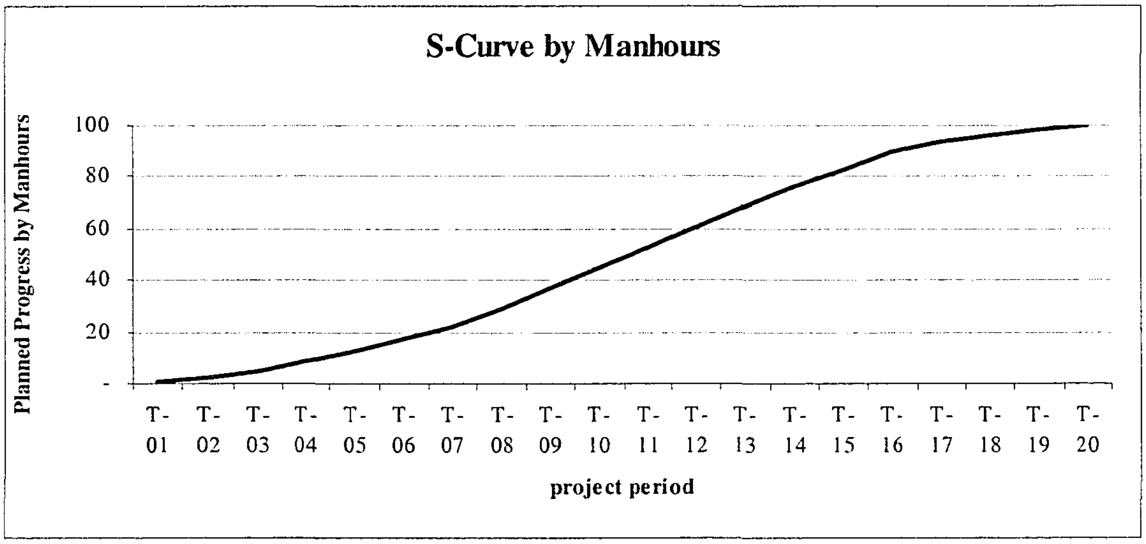


Figure A- 2 Planned S-Curve by Man-hours

2. *Project S-curve by Cost*

Using the cost budget and the schedule baseline, the cost S-Curve is obtained as shown below in figure A-3.

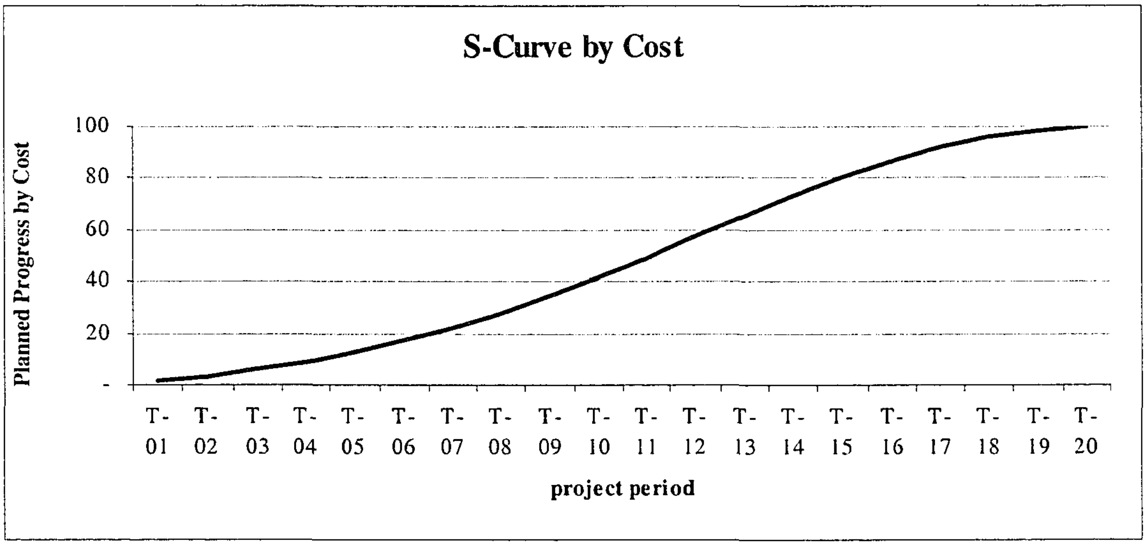


Figure A- 3 Planned S-Curve by Cost

3. *Project S-curve by Revenue*

Using the revenue amount and the schedule baseline, the revenue S-Curve is obtained as shown below in Figure A-4.

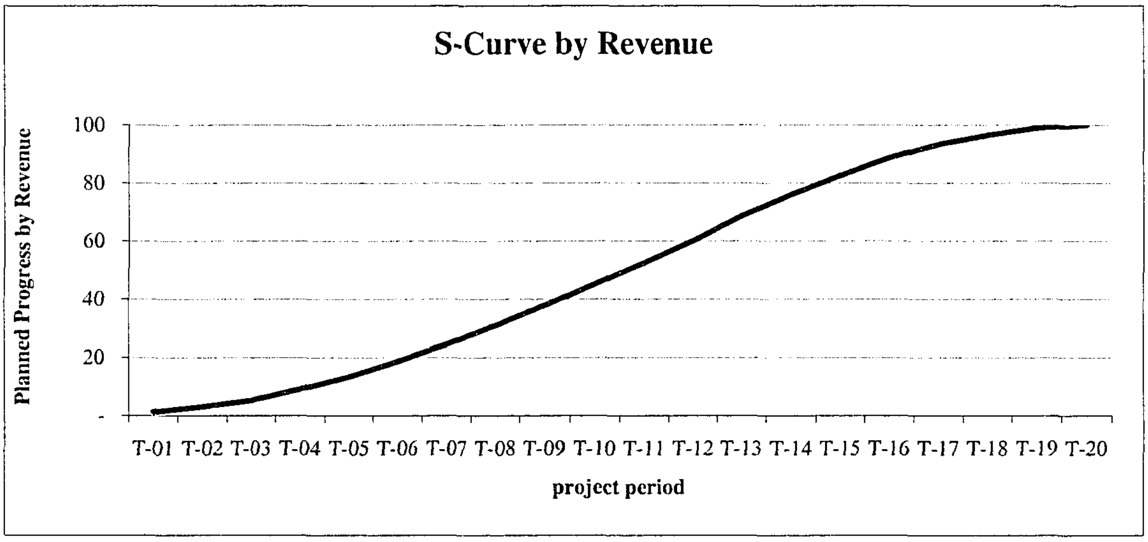


Figure A- 4 Planned S-Curve by Revenue

Step 2: Obtain actual and planned performance data

The actual data obtained from the project records as of a specific data date, assumed to be T-7 or at the end of the 7th week of the 20-week project, are listed in Table A-3.

Table A- 3 Actual data as of T-7

s/n	WP- Code	Description	Actual Physical Progress (%)	Spent Man-hours	Actual Cost of Work Performed	Actual Billed Amount
1	WP-01	Removal of existing pavement	100	810	192,305	189,860
2	WP-02	Excavation	100	530	69,907	79,988
3	WP-03	Subgrade compaction and backfilling	100	805	109,078	149,870
4	WP-04	Sub-base	90	1,100	155,288	153,780
5	WP-05	Basecourse	55	350	47,190	54,677
6	WP-06	Asphalt Pavement	8	70	37,566	52,456
7	WP-07	Concrete Pavement	0	-	-	-
8	WP-08	Manholes, gratings and drains	15	285	32,800	34,788
9	WP-09	Fences and gates	0	-	-	-
10	WP-10	General Finishing Works	0	-	-	-
11	WP-11	Electrical Works	12	480	87,890	78,972
		TOTAL		**4,430**	**732,024**	**794,391**

Based on the plan or project time baseline established and approved at the start of the project, the planned % figures as of T-7 are shown below:

Table A- 4 Planned data as of T-7

s/n	WP- Code	Description	Planned Progress (%)
1	WP-01	Removal of existing pavement	100
2	WP-02	Excavation	100
3	WP-03	Subgrade compaction and backfilling	100
4	WP-04	Sub-base	90
5	WP-05	Basecourse	55
6	WP-06	Asphalt Pavement	8
7	WP-07	Concrete Pavement	0
8	WP-08	Manholes, gratings and drains	15
9	WP-09	Fences and gates	0
10	WP-10	General Finishing Works	0
11	WP-11	Electrical Works	12
		TOTAL	

In addition to the above planned and actual data, the following actual safety performance figures are recorded as of the data date:

- LTI = Number of Lost Time Incidents to date = 0.
- M = Total man-hours expended to date = 4,430.

- The Total Cost of Rework is estimated to be $ 10,195.

The human resources department provided the team members satisfaction ratings as shown in Table A-5. The figures shown are the geometric mean of the individual team member ratings.

Table A- 5 Team Satisfaction Rating Table

No	Team Member Area of Concern	Satisfaction (1- 10)
1	Involvement in the project	7
2	Client/suppliers response to TM needs	6
3	Project Manager response to TM needs	8
4	Adequacy of equipment to get the work done	9
5	Training received to carry out the job	5
6	Financial compensation	5
7	Clarity of project related responsibilities	6
8	Quality of supervision	6
9	Interest in nature of work	7
10	Coordination with the various disciplines	8
11	Execution of work as per Company procedure	7
12	Access to Project Baselines & progress report	7

In addition, a formal survey, carried out the quality control department, reflected the degree of satisfaction of the client as shown in Table A-6.

Table A- 6 Client Satisfaction Rating

No	Client Area of Concern	Satisfaction (from 1- 10)
1	Understanding of the project requirements	8.5
2	Understanding of Client system & procedures	8
3	Response to the Client requests and/or needs	9
4	Flexibility and adjustment to changes	6
5	Overall capability of contractor project team	8.5
6	Effective communication	8.5
7	Innovation in problem solving	7
8	Performance with respect to cost	7
9	Performance with respect to schedule	9.5
10	Performance with respect to service quality	9
11	Performance with respect to product quality	9
12	Performance with respect to safety procedures	9.5

Step 3: Calculate the Earned Value

The earned value calculations, based on the above actual and planned data, are carried out as shown below. Table A-7 shows the Actual Cost of Work Performed (ACWP), the Budgeted Cost of Work Performed (BCWP), the Budgeted Cost of Work Scheduled (BCWS), the Billed Revenue for Work Performed (BRWP), and the Earned Revenue of Work Performed (ERWP).

Table A- 7 Earned Value calculations based on actual data

s/n	WP- Code	Description	ACWP	BCWP	BCWS	BRWP	ERWP
1	WP-01	Removal of existing pavement	192,305	172,209	172,209	189,860	196,157
2	WP-02	Excavation	69,907	74,950	74,950	79,988	82,404
3	WP-03	Subgrade compaction and backfilling	109,078	102,515	102,515	149,870	154,401
4	WP-04	Sub-base	155,288	132,398	125,043	153,780	152,236
5	WP-05	Basecourse	47,190	46,493	43,111	54,677	53,467
6	WP-06	Asphalt Pavement	37,566	40,075	25,047	52,456	53,138
7	WP-07	Concrete Pavement	-	-	-	-	-
8	WP-08	Manholes, gratings and drains	32,800	35,045	25,700	34,788	36,797
9	WP-09	Fences and gates	-	-	-	-	-
10	WP-10	General Finishing Works	-	-	-	-	-
11	WP-11	Electrical Works	87,890	76,003	63,336	78,972	79,802
		TOTAL	**732,024**	**679,687**	**631,910**	**794,391**	**808,402**

Project Completion by Man-hours at T-7

Table A-8 shows that the Budgeted Man hours for the Work Performed (BMWP) to date is 4,091 hours. In other word, the project is 24% (4,091/17,121) complete by man-hours as of T-7.

Table A- 8 Project Completion by Man-hours

s/n	WP- Code	Description	Actual Physical Progress (%)	Budgeted Manhours	Budgeted Manhours for Work Performed (BMWP)
1	WP-01	Removal of existing pavement	100	650	650
2	WP-02	Excavation	100	562	562
3	WP-03	Subgrade compaction and backfilling	100	769	769
4	WP-04	Sub-base	90	1,103	993
5	WP-05	Basecourse	55	634	349
6	WP-06	Asphalt Pavement	8	980	78
7	WP-07	Concrete Pavement	-	6,439	-
8	WP-08	Manholes, gratings and drains	15	1,752	263
9	WP-09	Fences and gates	-	184	-
10	WP-10	General Finishing Works	-	487	-
11	WP-11	Electrical Works	12	3,560	427
		TOTAL	**480**	**17,121**	**4,091**

Step 4: Calculate the Individual Performance Indices

Based on the above actual and earned value calculations, the eight performance indices are calculated as shown below:

1. Cost Performance Index

The Cost Performance Index (CPI) is defined by equation (2.5) and is calculated as of the project data date as follows:

CPI = BCWP/ ACWP = 679,687 / 732,024 = 0.93.

With reference to Table 2.1, the CPI is below target.

2. Schedule Performance Index (SPI)

The Schedule Performance Index (SPI) is defined by equation (2.8) and is calculated as of the data date as follows:

SPI = BCWP/ BCWS = 679,687 / 631,910 = 1.08.

With reference to Table 2.2, the SPI exceeds target.

3. Billing Performance Index (BPI)

The Billing Performance Index (BPI) is defined by equation (2.10) and is calculated as of the data date as follows:

BPI = BRWP/ ERWP = 794,391 / 808,402 = 0.98.

With reference to Table 2.3, the normalized BPI is equal to 1.11 or performance is above target.

4. Profitability Performance Index (PPI)

The Profitability Performance Index (BPI) is defined by equation (2.11) and is calculated as of the data date as follows:

PPI = ERWP/ ACWP = 808,402 / 732,024 = 1.10.

With reference to Figure 2.4, the normalized PPI is equal to 0.98 or performance is within target.

5. Safety Performance Index (SFI)

The non-normalized SFI is the Lost Time Incident (LTI) Frequency Rate defined as per Equation (2.12) and is calculated as of the data date as follows:

$$SFI = \frac{LTI * C}{M} = \frac{0 * 200{,}000}{4{,}430} = 0.$$

Where:

LTI = Number of Lost Time Incidents to date = 0

M = Total man-hours expended to date = 4,430 hours

C = 200,000 (a constant which represents 100 employees working for a full year).

With reference to Table 2.5, the normalized SFI is equal to 1.15 or outstanding performance. The project has achieved so far the objective of *zero (0)* site accidents.

6. Quality Performance Index (QPI)

The non-normalized QPI is given by:

QPI = CFRI = Construction Field Rework Index, where:

$$\text{CFRI} = \frac{\text{Total Direct and Indirect Cost of Rework performed in the Field}}{\text{Total Field Construction Phase Cost}} \quad \text{Equation (2.14)}$$

CFRI = \$10,195 / \$679,687 = 1.5 %.

With reference to Figure 2.6, the normalized QPI is equal to 1.0. This means that quality performance is within target.

7. Team Satisfaction Index (TSI)

In table A-9, the satisfaction value for each area of concern is determined by calculating the geometric mean of all the individual ratings. It should be noted that the priority weights are obtained using the AHP approach outlined in chapter 2 of this research. The earned rating for each member area of concern is shown in the following table.

Table A- 9 Project Team Satisfaction Rating

No	Team Member Area of Concern	Priority Wt.	Satisfaction (from 1- 10)	Earned Rating
1	Involvement in the project	0.06	7	0.42
2	Client/suppliers response to TM needs	0.07	6	0.42
3	Project Manager response to TM needs	0.09	8	0.72
4	Adequacy of equipment to get the work done	0.08	9	0.72
5	Training received to carry out the job	0.13	5	0.65
6	Financial compensation	0.16	5	0.80
7	Clarity of project related responsibilities	0.11	6	0.66
8	Quality of supervision	0.07	6	0.42
9	Interest in nature of work	0.08	7	0.56
10	Coordination with the various disciplines	0.05	8	0.40
11	Execution of work as per Company procedure	0.04	7	0.28
12	Access to Project Baselines & progress report	0.06	7	0.42

The summation of priority weights in the above table is 1 and the total of the earned ratings is 6.47. With reference to Figure 2.7, the normalized TSI is equal to 0.89; in other words, the team satisfaction is below target.

8. Client Satisfaction Index (CSI)

Table A-10 shows the satisfaction value for each area of concern as evaluated by the client team. It should be noted that the priority weights could be calculated by using the AHP approach as outlined in chapter 2 of this research or through objective assessment by the Client.

Table A- 10 Client Satisfaction Rating

No	Client Area of Concern	Priority Wt.	Satisfaction (from 1- 10)	Earned Rating
1	Understanding of the project requirements	0.11	8.5	0.94
2	Understanding of Client system & procedures	0.08	8	0.64
3	Response to the Client requests and/or needs	0.09	9	0.81
4	Flexibility and adjustment to changes	0.06	6	0.36
5	Overall capability of contractor project team	0.12	8.5	1.02
6	Effective communication	0.09	8.5	0.77
7	Innovation in problem solving	0.04	7	0.28
8	Performance with respect to cost	0.05	7	0.35
9	Performance with respect to schedule	0.10	9.5	0.95
10	Performance with respect to service quality	0.04	9	0.36
11	Performance with respect to product quality	0.11	9	0.99
12	Performance with respect to safety procedures	0.11	9.5	1.05

The summation of priority weights in the above table is 1.0 and the total of the earned ratings is 8.51. With reference to Figure 2.8, the normalized CSI is equal to 1.0, which means that client satisfaction is within target.

Step 5: Calculate the Overall Project Performance

The project performance index (PI) is given by Equations (2.19) as shown below.

$$PI = w_1 * CPI + w_2 * SPI + w_3 * BPI + w_4 * PPI + w_5 * SFI + w_6 * QPI + w_7 * TSI + w_8 * CSI \quad \text{Eq. (2.19)}$$

Where $\sum_{i=1}^{8} w_i = 1$ and

CPI, SPI, BPI, PPI, SFI, QPI, TSI, and CSI are the normalized performance indices as previously determined. $W_1 \ldots W8$ are the respective priority weights or relative importance with respect to the overall project performance (PI). These priority weights are derived using the AHP methodology as outlined in Section 2.6 of this research.

Using AHP to derive the Priority Weights

The Analytical hierarchy Process (AHP) was used successfully with the project team. Brainstorming and sharing ideas often lead to a better understanding of the issues. On the other hand, group sessions can also create many problems like unequal power and different expertise. In addition, the judgmental process in a group session will strain the minds of the participants over a short period of time. Because time is limited and to minimize the burden on the project team, a questionnaire was prepared in advance to obtain judgments (see appendix B) and the calculations were done afterwards. The questionnaire included the necessary instructions and a scale of importance to support the pair-wise judgments. The questionnaire was given to four of the project management team, namely the project manager, project engineer, planning engineer, and cost engineer.

Each of the 16 judgment matrices was tested for consistency as shown in Appendix C. A single matrix is constructed whose entries are obtained by taking the geometric mean of all the entries from the four matrices which is turn was tested for consistency and coherence of judgments. This is done for four points of project completion by man-hours: 0%, 30%, 60%, and 90%. Using interpolation, the priority weights are obtained at any period through out the project as demonstrated in Appendix D. Table A-11 shows the priority weights for the eight performance indices at 0%, 30%, 60%, and 90% of project completion by man hours

.

Table A- 11 Priority Weights for the performance indices at various progress points

	Priority Weights			
Index	At 0%	At 30%	At 60%	At 90%
CPI	0.2206	0.2013	0.1859	0.1862
SPI	0.1483	0.1825	0.1878	0.2029
BPI	0.1470	0.1175	0.1350	0.1312
PPI	0.1638	0.1433	0.1410	0.1467
SFI	0.1033	0.1254	0.1234	0.1216
QPI	0.0790	0.0911	0.0863	0.0710
TSI	0.0656	0.0632	0.0605	0.0625
CSI	0.0724	0.0758	0.0801	0.0780
Total	**1.00**	**1.00**	**1.00**	**1.00**

Referring to the above table and by interpolation, the values of the priority weights corresponding to 24% completion by man hours are: [w_1= 0.205, w_2= 0.176, w_3= 0.123, w_4= 0.147, w_5= 0.121, w_6= 0.089, w_7= 0.064, w_8= 0.075]. These weights show that cost performance has the highest priority and project team satisfaction has the lowest value. Based on these priorities, the overall performance as of T-7 can be calculated as follows:

$PI = w_1 *CPI+ w_2*SPI+ w_3*BPI+ w_4*PPI + w_5*SFI+ w_6*QPI+w_7*TSI+ w_8*CSI$

$PI = 0.205 *0.93+ 0.176*1.08+ 0.123*1.11+ 0.147*0.98 + 0.121*1.15+ 0.089*1.0 + 0.064*0.89+ 0.075*0.955$

$PI = 1.02$ or the overall performance is within target.

A-4 Forecasting Project Performance as of T-7 using Dynamic Markov Chains

The following section demonstrates in detail the cost forecasting process using *Dynamic Markov Chains* as explained in Chapter 3 of the thesis. Forecasting the other indices and the overall project performance index follows the same steps and is shown in summary.

A-4.1 Forecasting Cost Performance

In order to forecast the cost-at-completion or at any interim point in the project, the transition probability matrices need to be established.

A-4.1.1 Estimation of the Transition Probability Matrices and State Probabilities

The following four steps outline the procedure to calculate the Probability Transition Matrices and the State Probabilities at any time t for the Cost Performance Index (CPI).

Step 1. Estimation of the Initial Probability Vector

The initial probability distribution, at $t_1 = 0.05\ T$, is derived using the company records for similar past projects and using Equation (3.37). Assume that the company database consists of 20 similar past projects and shows the following information:

- Number of projects whose CPI in the first period was *outstanding* (State A) = 1.
- Number of projects whose CPI in the first period was *above target* (State B) = 2.
- Number of projects whose CPI in the first period was *within target* (State C) = 10.
- Number of projects whose CPI in the first period was *below target* (State D) = 6.
- Number of projects whose CPI in the first period was *poor* (State F) = 1.

Using the above historic statistics, the initial probability vector for the Cost Performance Index (CPI) can be calculated as follows:

$P_A\,(1)$ = 1/20 = 5%.

$P_B\,(1)$ = 2/20 = 10%.

$P_C\,(1) = 10/20 = 50\%$.

$P_D\,(1) = 6/20 = 30\%$.

$P_F\,(1) = 1/20 = 5\%$.

$P\,(1) = [5\%, 10\%, 50\%, 30\%, 5\%]$.

Step 2. Estimation of the Boundary Conditions

The boundary conditions for the cost performance transition probability curve, at $t_2 = 0.1\,T$, and $t_{20} = 1.0\,T$ are derived based on the company past records for an identical set of projects using Equations (3.41) & (3.42).

Transition Probabilities from State A

Assume that the historic database of the company shows that the number of projects with outstanding (State A) CPI at t_1 is 4. In addition the following data are collected:

$\mathbf{AA_2}$ = Number of projects whose CPI at $\boldsymbol{t_1=0.05T}$ was ***outstanding*** (State A) and continued to be ***outstanding*** (State A) at $\boldsymbol{t_2=0.1T}$ = 2.

$\mathbf{AB_2}$ = Number of projects whose CPI at $\boldsymbol{t_1=0.05T}$ was ***outstanding*** (State A) and transitioned to ***above target*** (State B) at $\boldsymbol{t_2=0.1T}$= 1.

$\mathbf{AC_2}$ = Number of projects whose CPI at $\boldsymbol{t_1=0.05T}$ was ***outstanding*** (State A) and transitioned to ***within target*** (State C) at $\boldsymbol{t_2=0.1T}$ = 1.

$\mathbf{AD_2}$ = Number of projects whose CPI at $\boldsymbol{t_1=0.05T}$ was ***outstanding*** (State A) and transitioned to ***below target*** (State D) at $\boldsymbol{t_2=0.1T}$ = nil.

$\mathbf{AF_2}$ = Number of projects whose CPI at $\boldsymbol{t_1=0.05T}$ was ***outstanding*** (State A) and transitioned to ***poor performance*** (State F) at $\boldsymbol{t_2=0.1T}$ = nil.

Based on above, the transition probabilities from state A to the other states at (t_2) can be calculated as follows:

$P_{AA}(t_2) = AA_2/5 = 2/4 = 0.5.$

$P_{AB}(t_2) = AB_2/5 = 1/4 = 0.25.$

$P_{AC}(t_2) = AC_2/5 = 1/4 = 0.25.$

$P_{AD}(t_2) = AD_2/5 = 0/4 = 0.$

$P_{AF}(t_2) = AF_2/5 = 0/4 = 0.$

Now, assume that the historic database of the company shows that the number of projects, where the CPI at t_{19} was outstanding (State A), is 10. In addition the following data are collected:

AA_{20} = Number of projects whose CPI at $t_{19}=0.95T$ was ***outstanding*** (State A) and continued to be ***outstanding*** (State A) at $t_{20}=1.0T$ = 9.

AB_{20} = Number of projects whose CPI at $t_{19}=0.95T$ was ***outstanding*** (State A) and transitioned to ***above target*** (State B) at $t_{20}=1.0T$= 1.

AC_{20} = Number of projects whose CPI at $t_{19}=0.95T$ was ***outstanding*** (State A) and transitioned to ***within target*** (State C) at $t_{20}=1.0T$ = nil.

AD_{20} = Number of projects whose CPI at $t_{19}=0.95T$ was ***outstanding*** (State A) and transitioned to ***below target*** (State D) at $t_{20}=1.0T$ = nil.

AF_{20} = Number of projects whose CPI at $t_{19}=0.95T$ was ***outstanding*** (State A) and transitioned to ***poor performance*** (State F) at $t_{20}=1.0T$ = nil.

The transition probabilities from state A to the other states at (t_{20}) are thus calculated as follows:

$P_{AA}(t_{20})$ = $AA_2/10 = 9/10 = 0.9$.

$P_{AB}(t_{20})$ = $AB_2/10 = 1/10 = 0.1$.

$P_{AC}(t_{20})$ = $AC_2/10 = 0/10 = 0$.

$P_{AD}(t_{20})$ = $AD_2/10 = 0/10 = 0$.

$P_{AF}(t_{20})$ = $AF_2/10 = 0/10 = 0$.

Using the same approach, the following transition probabilities are derived:

Transition Probabilities from State B

$P_{BA}(t_2) = 0.15$.

$P_{BB}(t_2) = 0.50$.

$P_{BC}(t_2) = 0.30$.

$P_{BD}(t_2) = 0.05$.

$P_{BF}(t_2) = 0$.

$P_{BA}(t_{20}) = 0.03$.

$P_{BB}(t_{20}) = 0.90$.

$P_{BC}(t_{20}) = 0.07$.

$P_{BD}(t_{20}) = 0$.

$P_{BF}(t_{20}) = 0$.

Transition Probabilities from State C

$P_{CA}(t_2) = 0.09$.

$P_{CB}(t_2) = 0.18$.

$P_{CC}(t_2) = 0.50$.

$P_{CD}(t_2) = 0.15$.

$P_{CF}(t_2) = 0.08$.

$P_{CA}\,(t_{20}) = 0.02.$

$P_{CB}\,(t_{20}) = 0.05.$

$P_{CC}\,(t_{20}) = 0.90.$

$P_{CD}\,(t_{20}) = 0.03.$

$P_{CF}\,(t_{20}) = 0.$

Transition Probabilities from State D

$P_{DA}\,(t_2) = 0.03.$

$P_{DB}\,(t_2) = 0.15.$

$P_{DC}\,(t_2) = 0.70.$

$P_{DD}\,(t_2) = 0.10$

$P_{DF}\,(t_2) = 0.02.$

$P_{DA}\,(t_{20}) = 0.$

$P_{DB}\,(t_{20}) = 0.$

$P_{DC}\,(t_{20}) = 0.08.$

$P_{DD}\,(t_{20}) = 0.9.$

$P_{DF}\,(t_{20}) = 0.02.$

Transition Probabilities from State F

$P_{FA}\,(t_2) = 0.$

$P_{FB}\,(t_2) = 0.02.$

$P_{FC}\,(t_2) = 0.08.$

$P_{FD}\,(t_2) = 0.75.$

$P_{FF}\,(t_2) = 0.15.$

$P_{FA}\,(t_{20}) = 0.$

$P_{FB}\,(t_{20}) = 0.$

$P_{FC}\,(t_{20}) = 0.01.$

$P_{FD}(t_{20}) = 0.09.$

$P_{FF}(t_{20}) = 0.90.$

Step 3. Estimation of the Transition Probability Curves

Using the initial and boundary conditions derived above and the planned S-Curve by Cost, the transition probability between any two states ***i*** and ***j***, at any time ***t***, can be calculated using Equation 3.44.

$$P_{ij}(t) = P_{ij}(t_2) - [P_{ij}(t_2) - P_{ij}(t_{20})] * [\, at^3 + bt^2 + ct + d\,] \qquad for \quad 2 < t < 20$$

$$For\ i, j = A, B, C, D, \&\ F. \qquad \text{Equation (3.44)}$$

Where $at^3 + bt^2 + ct + d$ is the equation of the planned Cost S-Curve. It displays the project cumulative cost as a function of time as shown in Table A-2.

Appendix (E) shows in detail the Transition Probability Curves for the Cost Performance Index.

Step 4. Estimation of the Probability of Future States of Cost Performance

The state probability vector at any time t is given by:

$P(t) = [\, P_A(t),\ P_B(t), P_C(t), P_D(t), P_F(t)\,]$

The state probability vector at time $t+1$ is given by:

$$P(t+1) = [\, P_A(t+1),\ P_B(t+1), P_C(t+1), P_D(t+1), P_F(t+1)\,] \qquad \text{Equation (3.45)}$$

But $P(t+1) = P(t) * [\, P\,]^{t+1}$ Equation (3.46)

Using the above equation, the probability of any future state can be forecasted.

For example, with reference to Equation (3.47), $P_A(t+1)$= Probability of ***outstanding*** performance at $t+1$ is:

$$=[P_A(t)*P_{AA}(t+1)+P_B(t)*P_{BA}(t+1)+P_C(t)*P_{CA}(t+1)+P_D(t)*P_{DA}(t+1)+P_F(t)*P_{FA}(t+1)]$$

$$=[P_A(t), P_B(t), P_C(t), P_D(t), P_F(t)] \text{ x } \begin{bmatrix} P_{AA}(t+1) \\ P_{BA}(t+1) \\ P_{CA}(t+1) \\ P_{DA}(t+1) \\ P_{FA}(t+1) \end{bmatrix}$$

To illustrate the above methodology, $P_A(3)$, the probability of having outstanding cost performance at period 3, is obtained as shown below:

$$P_A(3)=[P_A(2), P_B(2), P_C(2), P_D(2), P_F(2)] \text{ x } \begin{bmatrix} P_{AA}(3) \\ P_{BA}(3) \\ P_{CA}(3) \\ P_{DA}(3) \\ P_{FA}(3) \end{bmatrix}$$

$$=[9.40, 19.85, 50.65, 14.75, 5.35] \text{ x } \begin{bmatrix} 0.5240 \\ 0.1428 \\ 0.0858 \\ 0.0282 \\ 0 \end{bmatrix} = 12.52\%$$

Appendix E displays the calculations of the Transition Probability Curves and the State Probability Vector at any time ***t***.

A-4.1.2 Forecasting Cost-at-Completion as of T-7

As calculated above, the CPI as of T-7 is 0.93, which means that cost performance is *below target* or in state D. Substituting this performance figure into the model generates new figures and probabilities at completion as shown in Appendix F.

It should be noted that the planned S-Curve by cost is updated and revised based on the cumulative progress by cost using Equation (3.68). Assuming that the boundary conditions are still valid and that corrective action will be implemented by the project to bring performance back to target, the model forecasts the following:

- There is around 15% chance of having an ***outstanding*** cost performance at $t=20$.
- There is around 30% chance of having an ***above target*** cost performance at $t=20$.
- There is around 37% chance of having a ***within target*** cost performance at $t=20$.
- There is around 14% chance of having a ***below target*** cost performance at $t=20$.
- There is around 33% chance of cost performance staying ***below target*** at $t=8$.
- There is around 4% chance of having a ***poor*** cost performance at $t=20$.
- The expected Cost Performance Index (CPI) at $t=20$ is 1.039 or within target.

The above statistics show that the chance of staying ***below target*** next period is 33% and will drop to 14% at the end of the project as a result of the planned corrective action. In dollar value, the expected project cost at $t=20$ is $2,897,268/1.039 = $ 2,788,516. In other words, the expected cost saving is $108,752. For details refer to Appendix (F).

The following 3 scenarios will demonstrate the capabilities and functionality of the model.

Scenario 1: Progress update as of T-16: S-Curve and Transition Probabilities are not updated.

If the actual cumulative cost performance is 0.93 or ***below target*** as of T-16, then the expected Cost Performance Index (CPI) at $t=20$ will still be ***below target*** (0.936). Although corrective action is assumed to take place, it is too late to completely recover and get back to ***within target*** because most of the cost cannot be recovered. In this case, the following probabilities are calculated:

- There is less than 2% chance of having an ***outstanding*** cost performance at $t=20$.
- There is only 4% chance of having an ***above target*** cost performance at $t=20$.
- There is around 28% chance of having a ***within target*** cost performance at $t=20$.
- There is around 61% chance of having a ***below target*** cost performance at $t=20$.
- There is around 5% chance of having a ***poor*** cost performance at $t=20$.

In this case, the expected project cost at $t=20$ is \$2,897,268/0.936 = \$ 3,095,372. In other words, the expected cost overrun is \$198,104. Refer to Appendix G for details.

Scenario 2: Progress update as of T-16: S-Curve is updated and Transition Probabilities are not updated

Assume that the actual cumulative cost performance is 0.93 or ***below target*** as of T-16, and assume that the Budgeted Cost of Work Performed (BCWP) is 90.2% as of T-16 (vs. a planned value (BCWS) of 87%). As a result, the transition probabilities curves are adjusted to reflect the revised cost S-Curve. In this case, the expected Cost Performance Index (CPI) at $t=20$ drops from 0.936 to 0.931. This is due to the fact that the remaining scope of work decreased after the progress curve was updated. In this case, the following probabilities are calculated.

- There is around 1% chance of having an ***outstanding*** cost performance at *t=20.*
- There is around 3% chance of having an ***above target*** cost performance at *t=20.*
- There is around 26% chance of having a ***within target*** cost performance at *t=20.*
- There is around 64% chance of having a ***below target*** cost performance at *t=20.*
- There is around 6% chance of having a ***poor*** cost performance at *t=20.*

In this scenario, the expected project cost at *t=20* is $2,897,268/0.931 = $ 3,111,996 and the expected cost overrun will slightly increase to $214,728. Refer to Appendix (H) for details.

Scenario 3: Progress update as of T-16: Transition Probabilities are updated

Assume that the actual cumulative cost performance is 0.93 or ***below target*** as of T-16 and the actual progress is as planned. In this scenario, the transition probability curves are updated by the decision maker to reflect no or minimal corrective action and to incorporate the latest project conditions. As expected, this will negatively impact the expected Cost Performance Index (CPI) at *t=20* which is now 0.899. In this case, the following probabilities are calculated.

- There is less than 1% chance of having an ***outstanding*** cost performance at *t=20.*
- There is less than 2% chance of having an ***above target*** cost performance at *t=20.*
- There is around 20% chance of having a ***within target*** cost performance at *t=20.*
- There is around 50% chance of having a ***below target*** cost performance at *t=20.*
- There is around 27% chance of having a ***poor*** cost performance at *t=20.*

In this scenario, the expected project cost at *t=20* will increase to $2,897,268/0.899 = $ 3,222,768 and resulting in an expected cost overrun of $325,500. Refer to Appendix (I) for details.

A-4.2 Forecasting the Overall Project Performance at Completion

Applying the same approach for each of the remaining seven indices, we can forecast the project performance for each index as well as for the overall project index as shown in Table A-12. The priority weights at T=20 are obtained from Table A-11 based on the assumption that the priorities of the project team at completion will not differ from those at 90% progress by man hours.

Table A- 12 Forecast at-Completion

Index	**Description**	**Priority Wt. @ T=20**	**Forecasted Index Value at Completion**	**State**	**Earned Weight**
CPI	Cost Performance Index	0.1862	1.040	Within Target	0.19
SPI	Schedule Performance Index	0.2029	0.992	Within Target	0.20
BPI	Billing Performance Index	0.1312	1.145	Above Target	0.15
PPI	Profitability Performance Index	0.1467	1.039	Within Target	0.15
SFI	Safety Performance Index	0.1216	1.056	Above Target	0.13
QPI	Quality Performance Index	0.0710	1.014	Within Target	0.07
TSI	Project Team Satisfaction Index	0.0625	0.955	Within Target	0.06
CSI	Client Satisfaction Index	0.0780	0.999	Within Target	0.08
	TOTAL PERFORMANCE	**1.00**		**Within Target**	**1.04**

Table A-12 shows that the overall performance index is expected to be 1.04 or within target. This is based on the assumption that corrective action will be taken and will lead to better future performance. It should be noted that the future forecasted performance can be significantly impacted by the project input parameters like: (1) current cumulative progress, (2) timing and extent of future corrective action, and (3) user input and change in boundary conditions.

Forecasting Models for the other Performance Indices

To view the detailed calculations the reader should refer to Appendix (J), which includes the following models:

- Schedule Forecasting Model
- Schedule Forecasting Update
- Billing Forecasting Model
- Billing Forecasting Update
- Profitability Forecasting Model
- Profitability Forecasting Update
- Safety Forecasting Model
- Safety Forecasting Update
- Safety Forecasting Update – Scenario 1
- Quality Forecasting Model
- Quality Forecasting Update
- Team Satisfaction Forecasting Model
- Team Satisfaction Forecasting Update
- Client Satisfaction Forecasting Update
- Client Satisfaction Forecasting Update
- Client Satisfaction Forecasting Update – Scenario 1

APPENDIX (B)

AIIP Pair-wise Comparison Instruction Form

EXPERT JUDGMENTS

Project Performance Indices PI = Function (CPI, SPI, BPI, PPI, SFI, QPI, TSI, CSI)

CPI = Cost Performance Index

SPI = Schedule Performance Index

BPI = Billing Performance Index

PPI = Profitability Performance Index

SFI = Safety Performance Index

QPI = Quality Performance Index

TSI = *Project Team Satisfaction Index*

CSI = Client Satisfaction Index

A total of 8 Project Performance Indices

Matrix 1

	Matrix	INDEX 2								at t = 0 % , Start of Project
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI	Required :
I	CPI	1.00								Based on your experience and Judgment fill the adjacent matrix based on the **importance scale** described below by answering the following question: **"How much more important is Index 1 than Index 2 with respect to the Overall Project performance?"**
N	SPI	Calculated	1.00							
D	BPI	Calculated	Calculated	1.00						
E	PPI	Calculated	Calculated	Calculated	1.00					
X	SFI	Calculated	Calculated	Calculated	Calculated	1.00				
	QPI	Calculated	Calculated	Calculated	Calculated	Calculated	1.00			
1	TSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00		
	CSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00	

Matrix 2

	Matrix	INDEX 2								at t = 30 % Project Completion
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI	
I	CPI	1.00								
N	SPI	Calculated	1.00							
D	BPI	Calculated	Calculated	1.00						
E	PPI	Calculated	Calculated	Calculated	1.00					
X	SFI	Calculated	Calculated	Calculated	Calculated	1.00				
	QPI	Calculated	Calculated	Calculated	Calculated	Calculated	1.00			
1	TSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00		
	CSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00	

Matrix 3

	Matrix	INDEX 2								at t = 60 % Project Completion
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI	
I	CPI	1.00								
N	SPI	Calculated	1.00							
D	BPI	Calculated	Calculated	1.00						
E	PPI	Calculated	Calculated	Calculated	1.00					
X	SFI	Calculated	Calculated	Calculated	Calculated	1.00				
	QPI	Calculated	Calculated	Calculated	Calculated	Calculated	1.00			
1	TSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00		
	CSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00	

APPENDIX (B)

AHP Pair-wise Comparison Instruction Form

Matrix 4

	Matrix	INDEX 2								at t = 90 % Project Completion
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI	
I	CPI	1.00								
N	SPI	Calculated	1.00							
D	BPI	Calculated	Calculated	1.00						
E	PPI	Calculated	Calculated	Calculated	1.00					
X	SFI	Calculated	Calculated	Calculated	Calculated	1.00				
	QPI	Calculated	Calculated	Calculated	Calculated	Calculated	1.00			
1	TSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00		
	CSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00	

SCALE

INTENSITY OF IMPORTANCE SCALE		Intensity of Importance	Definition	Explanation
		1	Equal Importance	Two indices contribute **equally** to the Project Performance
		3	Weak importance of one over another	Index 1 is **slightly favored** over Index 2
		5	Medium Importance of one over another	Index 1 is **medium favored** over Index 2
		7	Strong Importance of one over another	Index 1 is **strongly favored** over Index 2
		9	Absolute Importance of one over another	Index 1 is **absolutely favored** over Index 2
		2,4,6,8	Intermediate values between the two adjacent judgments	when compromise is needed

	Matrix	INDEX 2								ILLUSTRATION
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI	**Required :**
I	CPI	1.00						4		Based on your experience and Judgment fill the adjacent matrix based on the importance scale described below by answering the following question : **"How much more important is Index 1 than Index 2 with respect to the Overall Project performance?"**
N	SPI	Calculated	1.00							
D	BPI	Calculated	Calculated	1.00	1/2					
E	PPI	Calculated	Calculated	2.00	1.00					
X	SFI	Calculated	Calculated	Calculated	Calculated	1.00				
	QPI	Calculated	Calculated	Calculated	Calculated	Calculated	1.00			
1	TSI	0.25	Calculated	Calculated	Calculated	Calculated	Calculated	1.00		
	CSI	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	Calculated	1.00	

▨ Calculated Fields

☐ Input Fields, to be entered by experts.

Example 1: If ,in your judgment ,the Cost Perofrmance Index (CPI) is 4 times more important than the Team Satsifaction Index (TSI) with respect to the Overall Project Performance (PI) then Enter "4" in (CPI,TSI) cell.

Example 2: If ,in your judgment , the Profitability Performance Index (PPI) is 2 times more important than the Billing Performance Index (BPI) with respect to the Overall Project Performance (PI) then Enter "1/2" in (BPI,PPI) cell.

APPENDIX (C)

EXPERT JUDGMENT CONSISTENCY CHECK

1 - Project Performance Indices

CPI = Cost Performance Index

SPI = Schedule Performance Index

BPI = Billing Performance Index

PPI = Profitability Performance Index

SFI = Safety Performance Index

QPI = Quality Performance Index

TSI = Project Team Satisfaction Index

CSI = Client Satisfaction Index

A total of **8** Project Performance Indices

2- Random Inconsistency Index Table (extracted from Table 2.18)

Matrix Size	**RI**
1	-
2	-
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

3- Judgment Matrix

		1	2	3	4	5	6	7	8
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
1	CPI	**1.00**	2.45	1.86	1.41	1.41	3.13	2.45	2.63
2	SPI	0.41	**1.00**	1.00	0.71	1.92	2.21	2.63	2.38
3	BPI	0.54	1.00	**1.00**	0.71	1.57	2.45	2.83	1.73
4	PPI	0.71	1.41	1.41	**1.00**	1.57	1.68	2.06	2.21
5	SFI	0.71	0.52	0.64	0.64	**1.00**	1.19	1.68	1.41
6	QPI	0.32	0.45	0.41	0.59	0.84	**1.00**	1.68	1.00
7	TSI	0.41	0.38	0.35	0.49	0.59	0.59	**1.00**	1.19
8	CSI	0.38	0.42	0.58	0.45	0.71	1.00	0.84	**1.00**
	total								
A	**76.95**	4.47	7.64	7.25	6.00	9.60	13.26	15.17	13.56
B	**0.98**	0.22	0.13	0.14	0.17	0.10	0.08	0.07	0.07
C	**1.00**	**0.23**	**0.13**	**0.14**	**0.17**	**0.11**	**0.08**	**0.07**	**0.08**

Crude Estimate of Eigen Vector				
Row Sum	Wt.Factor	Row Multiplication	N^{th} Root	Normalize N^{th} Root
16.35	0.21	184.02	1.92	0.2206
12.26	0.16	7.67	1.29	0.1483
11.82	0.15	7.14	1.28	0.1470
12.06	0.16	16.97	1.42	0.1638
7.79	0.10	0.43	0.90	0.1033
6.30	0.08	0.05	0.69	0.0790
5.01	0.07	0.01	0.57	0.0656
5.38	0.07	0.02	0.63	0.0724
76.95	**1.00**		**8.70**	**1.0000**

A = Column Sum

B = Reciprocal of "A"

C = Normalized Value of "B"

APPENDIX (C)

EXPERT JUDGMENT CONSISTENCY CHECK

4- Crude Estimate of Eigen Vector

Thr normalized Nth root is the eigen vector which represents the priority vector as shown below.

CPI	**0.221**
SPI	0.148
BPI	0.147
PPI	0.164
SFI	0.103
QPI	0.079
TSI	**0.066**
CSI	0.072
	1.000

Highest Priority	**0.221**	**CPI**
Lowest Priority	**0.066**	**TSI**

5- Crude Estimate of Max Eigen Value

Judgment Matrix

Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
CPI	**1.00**	2.45	1.86	1.41	1.41	3.13	2.45	2.63
SPI	0.41	**1.00**	1.00	0.71	1.92	2.21	2.63	2.38
BPI	0.54	1.00	**1.00**	0.71	1.57	2.45	2.83	1.73
PPI	0.71	1.41	1.41	**1.00**	1.57	1.68	2.06	2.21
SFI	0.71	0.52	0.64	0.64	**1.00**	1.19	1.68	1.41
QPI	0.32	0.45	0.41	0.59	0.84	**1.00**	1.68	1.00
TSI	0.41	0.38	0.35	0.49	0.59	0.59	**1.00**	1.19
CSI	0.38	0.42	0.58	0.45	0.71	1.00	0.84	**1.00**

X

Eigen Vector

V1
0.221
0.148
0.147
0.164
0.103
0.079
0.066
0.072

=

V2
1.834
1.219
1.196
1.327
0.842
0.643
0.538
0.585

→

V3=V2/V1
8.31
8.22
8.14
8.10
8.15
8.15
8.20
8.07

The Maximum Eigen Value (λ_{max}) is the Average of V3 = **8.17**

6- Crude Estimate of Consistency Ratio (CR)

CI - Consistency Index

As per Eq. (2.27) $CI = \mu \equiv \frac{\lambda_{max} - n}{n - 1} = 0.02395$

RI - Random Consistency Index

But RI , The Random Index (for a value of n = 8) = **1.41** As per Table 2. 18 Random Consistency Index Table

CR - Consistency Ratio

As per Equation (2.28) $CR = \frac{CI}{RC} =$ **0.02**

Since CR is < 0.10 , the judgments are consistent as per Saaty Criteria.

APPENDIX (D)

CONSOLIDATION OF EXPERT JUDGMENTS

Determine the Geometric Mean of Judgments at various stages of the project (I.e. 0%, 30%, 60%, and 90% completion points)

1- Calculate the Geometric Mean of Judgments @ T = 0% project completion

	at T = 0%	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	2.45	1.86	1.41	1.41	3.13	2.45	2.63
N	SPI	0.41	**1.00**	1.00	0.71	1.92	2.21	2.63	2.38
D	BPI	0.54	1.00	**1.00**	0.71	1.57	2.45	2.83	1.73
E	PPI	0.71	1.41	1.41	**1.00**	1.57	1.68	2.06	2.21
X	SFI	0.71	0.52	0.64	0.64	**1.00**	1.19	1.68	1.41
	QPI	0.32	0.45	0.41	0.59	0.84	**1.00**	1.68	1.00
1	TSI	0.41	0.38	0.35	0.49	0.59	0.59	**1.00**	1.19
	CSI	0.38	0.42	0.58	0.45	0.71	1.00	0.84	**1.00**

2- Calculate the Geometric Mean of Judgments @ T = 30% project completion

	at T = 30%	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	1.86	2.06	1.32	1.19	2.21	2.45	2.45
N	SPI	0.54	**1.00**	2.06	1.32	1.57	2.21	2.78	2.59
D	BPI	0.49	0.49	**1.00**	0.71	1.11	1.57	2.38	1.57
E	PPI	0.76	0.76	1.41	**1.00**	1.32	1.41	1.86	1.86
X	SFI	0.84	0.64	0.90	0.76	**1.00**	1.32	2.21	1.68
	QPI	0.45	0.45	0.64	0.71	0.76	**1.00**	1.68	1.19
1	TSI	0.41	0.36	0.42	0.54	0.45	0.59	**1.00**	0.84
	CSI	0.41	0.39	0.64	0.54	0.59	0.84	1.19	**1.00**

3- Calculate the Geometric Mean of Judgments @ T = 60% project completion

	at T = 60%	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	1.57	1.57	1.19	1.19	2.21	2.45	2.21
N	SPI	0.64	**1.00**	1.68	1.57	1.41	2.45	2.94	2.63
D	BPI	0.64	0.59	**1.00**	0.84	1.32	1.86	2.63	1.57
E	PPI	0.84	0.64	1.19	**1.00**	1.32	1.41	2.06	1.86
X	SFI	0.84	0.71	0.76	0.76	**1.00**	1.32	2.45	1.41
	QPI	0.45	0.41	0.54	0.71	0.76	**1.00**	1.68	1.00
1	TSI	0.41	0.34	0.38	0.49	0.41	0.59	**1.00**	0.84
	CSI	0.45	0.38	0.64	0.54	0.71	1.00	1.19	**1.00**

4- Calculate the Geometric Mean of Judgments @ T = 90% project completion

	at T = 90%	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	1.41	1.57	1.19	1.19	2.78	2.45	2.21
N	SPI	0.71	**1.00**	1.68	1.86	1.57	3.34	3.08	2.63
D	BPI	0.64	0.59	**1.00**	0.71	1.32	2.34	2.21	1.57
E	PPI	0.84	0.54	1.41	**1.00**	1.32	1.97	2.28	1.86
X	SFI	0.84	0.64	0.76	0.76	**1.00**	1.57	2.06	1.57
	QPI	0.36	0.30	0.43	0.51	0.64	**1.00**	1.41	1.00
1	TSI	0.41	0.32	0.45	0.44	0.49	0.71	**1.00**	0.84
	CSI	0.45	0.38	0.64	0.54	0.64	1.00	1.19	**1.00**

APPENDIX (D)

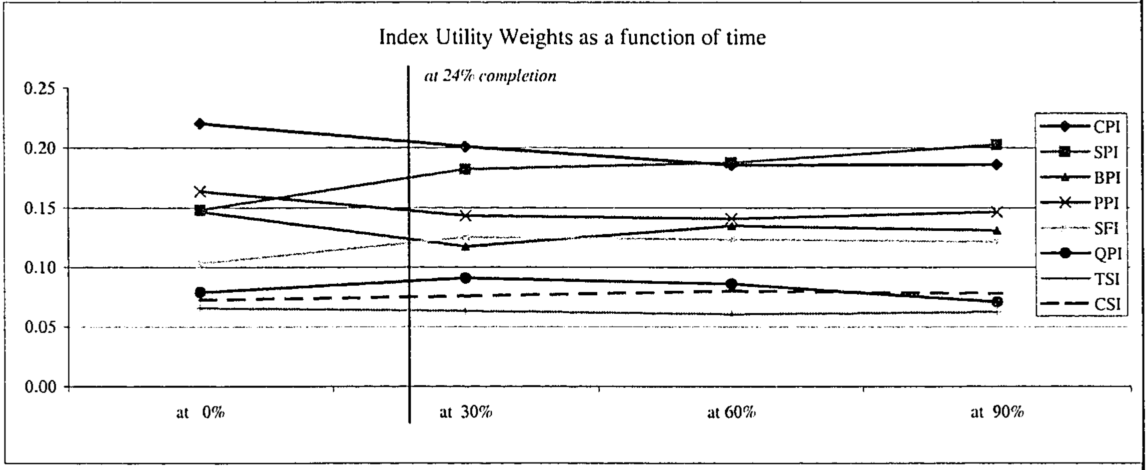
CONSOLIDATION OF EXPERT JUDGMENTS

5- Calculate the Priority Weights for each Performance Index as a function of time

	Priority Weights				
Index	at 0%	at 30%	at 60%	at 90%	at 24%
CPI	0.2206	0.2013	0.1859	0.1862	0.205
SPI	0.1483	0.1825	0.1878	0.2029	0.176
BPI	0.1470	0.1175	0.1350	0.1312	0.123
PPI	0.1638	0.1433	0.1410	0.1467	0.147
SFI	0.1033	0.1254	0.1234	0.1216	0.121
QPI	0.0790	0.0911	0.0863	0.0710	0.089
TSI	0.0656	0.0632	0.0605	0.0625	0.064
CSI	0.0724	0.0758	0.0801	0.0780	0.075
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Note: The Geometric Mean is used to calculate the average of the range of expert judgments. The Reciprocal Value of the Geometric Mean of the set of judgments is equivalent to the Geometric Mean of the Reciprocal Values of the judgments.

It is assumed that the weights at 90% are the same at 100% or project completion.



APPENDIX (D)

CONSOLIDATION OF EXPERT JUDGMENTS

At t = 0% Completion

	Expert 1	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	2.00	1.00	1.00	1.00	4.00	3.00	4.00
N	SPI	0.50	**1.00**	0.50	0.50	3.00	2.00	4.00	4.00
D	BPI	1.00	2.00	**1.00**	0.50	2.00	3.00	4.00	3.00
E	PPI	1.00	2.00	2.00	**1.00**	2.00	2.00	3.00	4.00
X	SFI	1.00	0.33	0.50	0.50	**1.00**	1.00	2.00	2.00
	QPI	0.25	0.50	0.33	0.50	1.00	**1.00**	2.00	1.00
1	TSI	0.33	0.25	0.25	0.33	0.50	0.50	**1.00**	2.00
	CSI	0.25	0.25	0.33	0.25	0.50	1.00	0.50	**1.00**

	Expert 2	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	3.00	4.00	4.00	2.00	2.00	2.00	1.00
N	SPI	0.33	**1.00**	2.00	2.00	1.00	2.00	2.00	1.00
D	BPI	0.25	0.50	**1.00**	1.00	1/2	1.00	1.00	0.50
E	PPI	0.25	0.50	1.00	**1.00**	1/2	1.00	1.00	0.50
X	SFI	0.50	1.00	2.00	2.00	**1.00**	1.00	1.00	1.00
	QPI	0.50	0.50	1.00	1.00	1.00	**1.00**	1.00	1.00
1	TSI	0.50	0.50	1.00	1.00	1.00	1.00	**1.00**	0.50
	CSI	1.00	1.00	2.00	2.00	1.00	1.00	2.00	**1.00**

	Expert 3	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	3.00	3.00	1.00	2.00	3.00	2.00	3.00
N	SPI	0.33	**1.00**	2.00	0.50	1.50	3.00	1.50	2.00
D	BPI	0.33	0.50	**1.00**	1.00	3.00	4.00	4.00	2.00
E	PPI	1.00	2.00	1.00	**1.00**	3.00	2.00	2.00	3.00
X	SFI	0.50	0.67	0.33	0.33	**1.00**	2.00	2.00	1.00
	QPI	0.33	0.33	0.25	0.50	0.50	**1.00**	2.00	1.00
1	TSI	0.50	0.67	0.25	0.50	0.50	0.50	**1.00**	1.00
	CSI	0.33	0.50	0.50	0.33	1.00	1.00	1.00	**1.00**

	Expert 4	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	2.00	1.00	1.00	1.00	4.00	3.00	4.00
N	SPI	0.50	**1.00**	0.50	0.50	3.00	2.00	4.00	4.00
D	BPI	1.00	2.00	**1.00**	0.50	2.00	3.00	4.00	3.00
E	PPI	1.00	2.00	2.00	**1.00**	2.00	2.00	3.00	4.00
X	SFI	1.00	0.33	0.50	0.50	**1.00**	1.00	2.00	2.00
	QPI	0.25	0.50	0.33	0.50	1.00	**1.00**	2.00	1.00
1	TSI	0.33	0.25	0.25	0.33	0.50	0.50	**1.00**	2.00
	CSI	0.25	0.25	0.33	0.25	0.50	1.00	0.50	**1.00**

At 30% Completion

	Expert 1	INDEX 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	2.00	1.00	1.00	1.00	4.00	3.00	4.00
N	SPI	0.50	**1.00**	1.00	1.00	4.00	3.00	5.00	5.00
D	BPI	1.00	1.00	**1.00**	0.50	2.00	3.00	4.00	3.00
E	PPI	1.00	1.00	2.00	**1.00**	2.00	2.00	3.00	4.00
X	SFI	1.00	0.25	0.50	0.50	**1.00**	1.00	2.00	2.00
	QPI	0.25	0.33	0.33	0.50	1.00	**1.00**	2.00	1.00
1	TSI	0.33	0.20	0.25	0.33	0.50	0.50	**1.00**	2.00
	CSI	0.25	0.20	0.33	0.25	0.50	1.00	0.50	**1.00**

APPENDIX (D)

CONSOLIDATION OF EXPERT JUDGMENTS

	Expert 2	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	2.00	3.00	3.00	1.00	2.00	2.00	1.00
N	SPI	0.50	**1.00**	3.00	2.00	1.00	2.00	2.00	1.00
D	BPI	0.33	0.33	**1.00**	1.00	1/2	1.00	1.00	1/2
E	PPI	0.33	0.50	1.00	**1.00**	1/2	1.00	1.00	1/2
X	SFI	1.00	1.00	2.00	2.00	**1.00**	1.00	2.00	1.00
	QPI	0.50	0.50	1.00	1.00	1.00	**1.00**	1.00	1.00
1	TSI	0.50	0.50	1.00	1.00	0.50	1.00	**1.00**	1/2
	CSI	1.00	1.00	2.00	2.00	1.00	1.00	2.00	**1.00**

	Expert 3	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	3.00	3.00	1.00	2.00	3.00	2.00	3.00
N	SPI	0.33	**1.00**	3.00	1.50	1.50	4.00	2.00	3.00
D	BPI	0.33	0.33	**1.00**	1.00	3.00	4.00	4.00	2.00
E	PPI	1.00	0.67	1.00	**1.00**	3.00	2.00	2.00	3.00
X	SFI	0.50	0.67	0.33	0.33	**1.00**	3.00	3.00	2.00
	QPI	0.33	0.25	0.25	0.50	0.33	**1.00**	2.00	1.00
1	TSI	0.50	0.50	0.25	0.50	0.33	0.50	**1.00**	1.00
	CSI	0.33	0.33	0.50	0.33	0.50	1.00	1.00	**1.00**

	Expert 4	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	1.00	2.00	1.00	1.00	1.00	3.00	3.00
N	SPI	1.00	**1.00**	2.00	1.00	1.00	1.00	3.00	3.00
D	BPI	0.50	0.50	**1.00**	1/2	1/2	1/2	2.00	2.00
E	PPI	1.00	1.00	2.00	**1.00**	1.00	1.00	2.00	2.00
X	SFI	1.00	1.00	2.00	1.00	**1.00**	1.00	2.00	2.00
	QPI	1.00	1.00	2.00	1.00	1.00	**1.00**	2.00	2.00
1	TSI	0.33	0.33	0.50	0.50	0.50	0.50	**1.00**	1/2
	CSI	0.33	0.33	0.50	0.50	0.50	0.50	2.00	**1.00**

At 60% Completion

	Expert 1	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	2.00	1.00	1.00	1.00	4.00	3.00	4.00
N	SPI	0.50	**1.00**	1.00	1.50	4.00	4.00	5.00	6.00
D	BPI	1.00	1.00	**1.00**	0.50	2.00	3.00	4.00	3.00
E	PPI	1.00	0.67	2.00	**1.00**	2.00	2.00	3.00	4.00
X	SFI	1.00	0.25	0.50	0.50	**1.00**	1.00	2.00	2.00
	QPI	0.25	0.25	0.33	0.50	1.00	**1.00**	2.00	1.00
1	TSI	0.33	0.20	0.25	0.33	0.50	0.50	**1.00**	2.00
	CSI	0.25	0.17	0.33	0.25	0.50	1.00	0.50	**1.00**

	Expert 2	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	1.00	2.00	2.00	1.00	1.00	2.00	1.00
N	SPI	1.00	**1.00**	2.00	2.00	1/2	1.00	2.00	1.00
D	BPI	0.50	0.50	**1.00**	1.00	1/2	1/2	1.00	1/2
E	PPI	0.50	0.50	1.00	**1.00**	1/2	1/2	1.00	1/2
X	SFI	1.00	2.00	2.00	2.00	**1.00**	1.00	2.00	1.00
	QPI	1.00	1.00	2.00	2.00	1.00	**1.00**	1.00	1.00
1	TSI	0.50	0.50	1.00	1.00	0.50	1.00	**1.00**	1/2
	CSI	1.00	1.00	2.00	2.00	1.00	1.00	2.00	**1.00**

APPENDIX (D)

CONSOLIDATION OF EXPERT JUDGMENTS

	Expert 3	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	3.00	3.00	1.00	2.00	3.00	2.00	3.00
N	SPI	0.33	**1.00**	4.00	2.00	2.00	4.50	2.50	4.00
D	BPI	0.33	0.25	**1.00**	1.00	3.00	4.00	4.00	2.00
E	PPI	1.00	0.50	1.00	**1.00**	3.00	2.00	2.00	3.00
X	SFI	0.50	0.50	0.33	0.33	**1.00**	3.00	3.00	2.00
	QPI	0.33	0.22	0.25	0.50	0.33	**1.00**	2.00	1.00
1	TSI	0.50	0.40	0.25	0.50	0.33	0.50	**1.00**	1.00
	CSI	0.33	0.25	0.50	0.33	0.50	1.00	1.00	**1.00**

	Expert 4	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	1.00	1.00	1.00	1.00	2.00	3.00	2.00
N	SPI	1.00	**1.00**	1.00	1.00	1.00	2.00	3.00	2.00
D	BPI	1.00	1.00	**1.00**	1.00	1.00	2.00	3.00	2.00
E	PPI	1.00	1.00	1.00	**1.00**	1.00	2.00	3.00	2.00
X	*SFI*	*1.00*	*1.00*	*1.00*	*1.00*	***1.00***	*1.00*	3.00	*1.00*
	QPI	0.50	0.50	0.50	0.50	1.00	**1.00**	2.00	1.00
1	TSI	0.33	0.33	0.33	0.33	0.33	0.50	**1.00**	1/2
	CSI	0.50	0.50	0.50	0.50	1.00	1.00	2.00	**1.00**

At 90% Completion

	Expert 1	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	2.00	1.00	1.00	1.00	4.00	3.00	4.00
N	SPI	0.50	**1.00**	1.00	2.00	4.00	5.00	5.00	6.00
D	BPI	1.00	1.00	**1.00**	0.50	2.00	3.00	4.00	3.00
E	PPI	1.00	0.50	2.00	**1.00**	2.00	2.00	3.00	4.00
X	SFI	1.00	0.25	0.50	0.50	**1.00**	2.00	3.00	3.00
	QPI	0.25	0.20	0.33	0.50	0.50	**1.00**	2.00	1.00
1	TSI	0.33	0.20	0.25	0.33	0.33	0.50	**1.00**	2.00
	CSI	0.25	0.17	0.33	0.25	0.33	1.00	0.50	**1.00**

	Expert 2	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.0**	1.0	2.0	2.0	1.0	1.0	2.0	1.0
N	SPI	1.0	**1.0**	2.0	2.0	0.5	1.0	2.0	1.0
D	BPI	0.5	0.5	**1.0**	1.0	0.5	0.5	0.5	0.5
E	PPI	0.5	0.5	1.0	**1.0**	0.5	0.5	1.0	0.5
X	SFI	1.0	2.0	2.0	2.0	**1.0**	1.0	2.0	1.0
	QPI	1.0	1.0	2.0	2.0	1.0	**1.0**	1.0	1.0
1	TSI	0.5	0.5	2.0	1.0	0.5	1.0	**1.0**	0.5
	CSI	1.0	1.0	2.0	2.0	1.0	1.0	2.0	**1.0**

	Expert 3	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	2.00	3.00	1.00	2.00	3.00	2.00	3.00
N	SPI	0.50	**1.00**	4.00	3.00	3.00	5.00	3.00	4.00
D	BPI	0.33	0.25	**1.00**	0.50	3.00	4.00	4.00	2.00
E	PPI	1.00	0.33	2.00	**1.00**	3.00	3.00	3.00	3.00
X	SFI	0.50	0.33	0.33	0.33	**1.00**	3.00	3.00	2.00
	QPI	0.33	0.20	0.25	0.33	0.33	**1.00**	2.00	1.00
1	TSI	0.50	0.33	0.25	0.33	0.33	0.50	**1.00**	1.00
	CSI	0.33	0.25	0.50	0.33	0.50	1.00	1.00	**1.00**

	Expert 4	I N D E X 2							
	Performance Indices	CPI	SPI	BPI	PPI	SFI	QPI	TSI	CSI
I	CPI	**1.00**	1.00	1.00	1.00	1.00	5.00	3.00	2.00
N	SPI	1.00	**1.00**	1.00	1.00	1.00	5.00	3.00	2.00
D	BPI	1.00	1.00	**1.00**	1.00	1.00	5.00	3.00	2.00
E	PPI	1.00	1.00	1.00	**1.00**	1.00	5.00	3.00	2.00
X	SFI	1.00	1.00	1.00	1.00	**1.00**	1.00	1.00	1.00
	QPI	0.20	0.20	0.20	0.20	1.00	**1.00**	1.00	1.00
1	TSI	0.33	0.33	0.33	0.33	1.00	1.00	**1.00**	1/2
	CSI	0.50	0.50	0.50	0.50	1.00	1.00	2.00	**1.00**

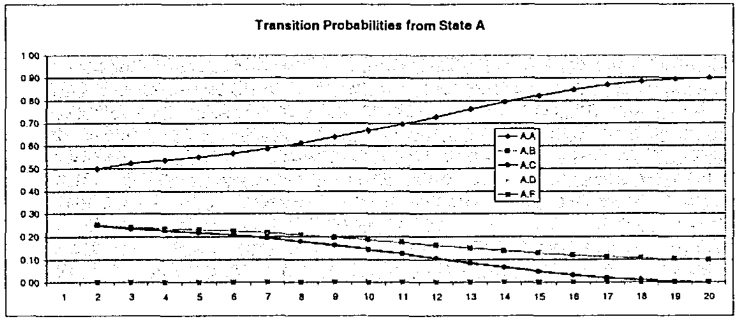
Appendix (E): Cost Forecasting Model

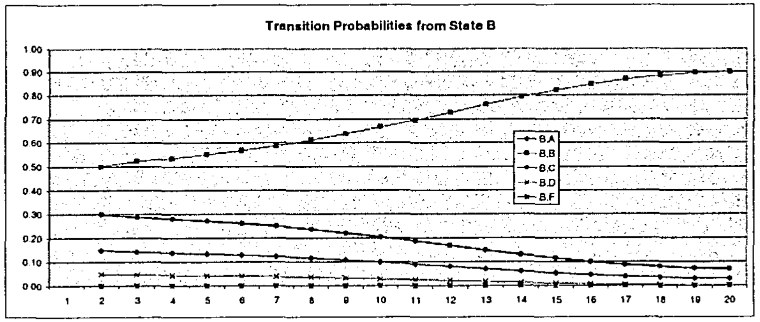
Forecasting Project Performance using Dynamic Markov Chains COST

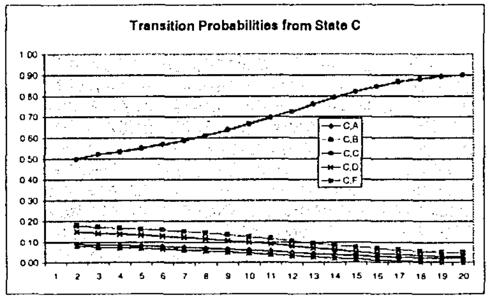
Transition Probabilities as a Function of Project Duration (T)

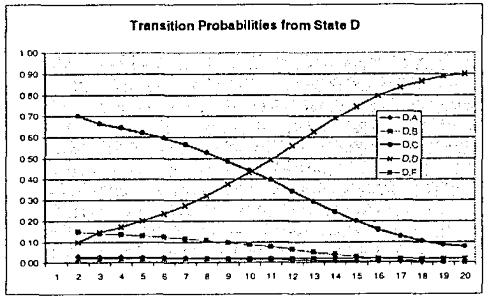
boundary conditions derived based on company historic database

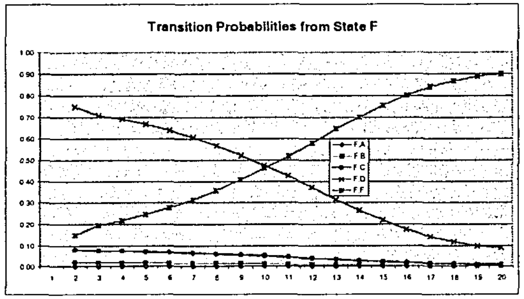
S-Curve By Cost	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.50	1	at t = 0.05 T																									
3.50	2	at t = 0.10 T	0.5000	0.2500	0.2500	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1800	0.5000	0.1500	0.0800	0.0300	0.1500	0.7000	0.1000	0.0200	-	0.0200	0.0800	0.7500	0.1500
6.00	3	at t = 0.15 T	0.5240	0.2410	0.2350	-	-	0.1428	0.5240	0.2862	0.0470	-	0.0858	0.1722	0.5240	0.1428	0.0752	0.0282	0.1410	0.6628	0.1480	0.0200	-	0.0188	0.0758	0.7104	0.1950
9.00	4	at t = 0.20 T	0.5360	0.2365	0.2275	-	-	0.1392	0.5360	0.2793	0.0455	-	0.0837	0.1683	0.5360	0.1392	0.0728	0.0273	0.1365	0.6442	0.1720	0.0200	-	0.0182	0.0737	0.6906	0.2175
12.80	5	at t = 0.25 T	0.5512	0.2308	0.2180	-	-	0.1346	0.5512	0.2706	0.0436	-	0.0810	0.1634	0.5512	0.1346	0.0698	0.0262	0.1308	0.6206	0.2024	0.0200	-	0.0174	0.0710	0.6655	0.2460
17.00	6	at t = 0.30 T	0.5680	0.2245	0.2075	-	-	0.1296	0.5680	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664	0.0249	0.1245	0.5946	0.2360	0.0200	-	0.0166	0.0681	0.6378	0.2775
21.80	7	at t = 0.35 T	0.5872	0.2173	0.1955	-	-	0.1238	0.5872	0.2499	0.0391	-	0.0747	0.1517	0.5872	0.1238	0.0626	0.0235	0.1173	0.5648	0.2744	0.0200	-	0.0156	0.0647	0.6061	0.3135
27.80	8	at t = 0.40 T	0.6112	0.2083	0.1805	-	-	0.1166	0.6112	0.2361	0.0361	-	0.0705	0.1439	0.6112	0.1166	0.0578	0.0217	0.1083	0.5276	0.3224	0.0200	-	0.0144	0.0605	0.5665	0.3585
34.60	9	at t = 0.45 T	0.6384	0.1981	0.1635	-	-	0.1085	0.6384	0.2204	0.0327	-	0.0658	0.1350	0.6384	0.1085	0.0523	0.0196	0.0981	0.4855	0.3768	0.0200	-	0.0131	0.0558	0.5216	0.4095
41.70	10	at t = 0.50 T	0.6668	0.1875	0.1458	-	-	0.1000	0.6668	0.2041	0.0292	-	0.0608	0.1258	0.6668	0.1000	0.0466	0.0175	0.0875	0.4415	0.4336	0.0200	-	0.0117	0.0508	0.4748	0.4628
48.90	11	at t = 0.55 T	0.6956	0.1767	0.1278	-	-	0.0913	0.6956	0.1875	0.0256	-	0.0558	0.1164	0.6956	0.0913	0.0409	0.0153	0.0767	0.3968	0.4912	0.0200	-	0.0102	0.0458	0.4273	0.5168
57.20	12	at t = 0.60 T	0.7288	0.1642	0.1070	-	-	0.0814	0.7288	0.1684	0.0214	-	0.0500	0.1056	0.7288	0.0814	0.0342	0.0128	0.0642	0.3454	0.5576	0.0200	-	0.0086	0.0400	0.3725	0.5790
65.70	13	at t = 0.65 T	0.7628	0.1515	0.0858	-	-	0.0712	0.7628	0.1489	0.0172	-	0.0440	0.0946	0.7628	0.0712	0.0274	0.0103	0.0515	0.2927	0.6256	0.0200	-	0.0069	0.0340	0.3164	0.6428
73.50	14	at t = 0.70 T	0.7940	0.1398	0.0663	-	-	0.0618	0.7940	0.1310	0.0133	-	0.0386	0.0845	0.7940	0.0618	0.0212	0.0080	0.0398	0.2443	0.6880	0.0200	-	0.0053	0.0286	0.2649	0.7013
80.50	15	at t = 0.75 T	0.8220	0.1293	0.0488	-	-	0.0534	0.8220	0.1149	0.0098	-	0.0337	0.0754	0.8220	0.0534	0.0156	0.0059	0.0293	0.2009	0.7440	0.0200	-	0.0039	0.0237	0.2187	0.7538
87.00	16	at t = 0.80 T	0.8480	0.1195	0.0325	-	-	0.0456	0.8480	0.0999	0.0065	-	0.0291	0.0669	0.8480	0.0456	0.0104	0.0039	0.0195	0.1606	0.7960	0.0200	-	0.0026	0.0191	0.1758	0.8025
92.20	17	at t = 0.85 T	0.8688	0.1117	0.0195	-	-	0.0394	0.8688	0.0879	0.0039	-	0.0255	0.0601	0.8688	0.0394	0.0062	0.0023	0.0117	0.1284	0.8376	0.0200	-	0.0016	0.0155	0.1415	0.8415
95.70	18	at t = 0.90 T	0.8828	0.1065	0.0108	-	-	0.0352	0.8828	0.0799	0.0022	-	0.0230	0.0556	0.8828	0.0352	0.0034	0.0013	0.0064	0.1067	0.8656	0.0200	-	0.0009	0.0130	0.1184	0.8678
98.70	19	at t = 0.95 T	0.8948	0.1020	0.0033	-	-	0.0316	0.8948	0.0730	0.0006	-	0.0209	0.0517	0.8948	0.0316	0.0010	0.0004	0.0020	0.0881	0.8896	0.0200	-	0.0003	0.0109	0.0986	0.8903
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0800	0.9000	0.0200	-	-	0.0100	0.0900	0.9000


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

Appendix (E): Cost Forecasting Model

Forecasting Project Performance using Dynamic Markov Chains

COST

	at t = 0.05 T				
	A	B	C	D	F
A					
B					
C					
D					
F					

	at t = 0.10 T				
	A	B	C	D	F
A	**0.5000**	**0.2500**	**0.2500**	-	-
B	**0.1500**	**0.5000**	**0.3000**	**0.0500**	-
C	**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**
D	**0.0300**	**0.1500**	**0.7000**	**0.1000**	**0.0200**
F	-	**0.0200**	**0.0800**	**0.7500**	**0.1500**

	at t = 0.15 T				
	A	B	C	D	F
A	0.5240	0.2410	0.2350	-	-
B	0.1428	0.5240	0.2862	0.0470	-
C	0.0858	0.1722	0.5240	0.1428	0.0752
D	0.0282	0.1410	0.6628	0.1480	0.0200
F	-	0.0188	0.0758	0.7104	0.1950

	at t = 0.20 T				
	A	B	C	D	F
A	0.5360	0.2365	0.2275	-	-
B	0.1392	0.5360	0.2793	0.0455	-
C	0.0837	0.1683	0.5360	0.1392	0.0728
D	0.0273	0.1365	0.6442	0.1720	0.0200
F	-	0.0182	0.0737	0.6906	0.2175

	at t = 0.25 T				
	A	B	C	D	F
A	0.5512	0.2308	0.2180	-	-
B	0.1346	0.5512	0.2706	0.0436	-
C	0.0810	0.1634	0.5512	0.1346	0.0698
D	0.0262	0.1308	0.6206	0.2024	0.0200
F	-	0.0174	0.0710	0.6655	0.2460

	at t = 0.30 T				
	A	B	C	D	F
A	0.5680	0.2245	0.2075	-	-
B	0.1296	0.5680	0.2609	0.0415	-
C	0.0781	0.1579	0.5680	0.1296	0.0664
D	0.0249	0.1245	0.5946	0.2360	0.0200
F	-	0.0166	0.0681	0.6378	0.2775

	at t = 0.35 T				
	A	B	C	D	F
A	0.5872	0.2173	0.1955	-	-
B	0.1238	0.5872	0.2499	0.0391	-
C	0.0747	0.1517	0.5872	0.1238	0.0626
D	0.0235	0.1173	0.5648	0.2744	0.0200
F	-	0.0156	0.0647	0.6061	0.3135

	at t = 0.40 T				
	A	B	C	D	F
A	0.6112	0.2083	0.1805	-	-
B	0.1166	0.6112	0.2361	0.0361	-
C	0.0705	0.1439	0.6112	0.1166	0.0578
D	0.0217	0.1083	0.5276	0.3224	0.0200
F	-	0.0144	0.0605	0.5665	0.3585

	at t = 0.45 T				
	A	B	C	D	F
A	0.6384	0.1981	0.1635	-	-
B	0.1085	0.6384	0.2204	0.0327	-
C	0.0658	0.1350	0.6384	0.1085	0.0523
D	0.0196	0.0981	0.4855	0.3768	0.0200
F	-	0.0131	0.0558	0.5216	0.4095

	at t = 0.50 T				
	A	B	C	D	F
A	0.6668	0.1875	0.1458	-	-
B	0.1000	0.6668	0.2041	0.0292	-
C	0.0608	0.1258	0.6668	0.1000	0.0466
D	0.0175	0.0875	0.4415	0.4336	0.0200
F	-	0.0117	0.0508	0.4748	0.4628

	at t = 0.55 T				
	A	B	C	D	F
A	0.6956	0.1767	0.1278	-	-
B	0.0913	0.6956	0.1875	0.0256	-
C	0.0558	0.1164	0.6956	0.0913	0.0409
D	0.0153	0.0767	0.3968	0.4912	0.0200
F	-	0.0102	0.0458	0.4273	0.5168

	at t = 0.60 T				
	A	B	C	D	F
A	0.7288	0.1642	0.1070	-	-
B	0.0814	0.7288	0.1684	0.0214	-
C	0.0500	0.1056	0.7288	0.0814	0.0342
D	0.0128	0.0642	0.3454	0.5576	0.0200
F	-	0.0086	0.0400	0.3725	0.5790

	at t = 0.65 T				
	A	B	C	D	F
A	0.7628	0.1515	0.0858	-	-
B	0.0712	0.7628	0.1489	0.0172	-
C	0.0440	0.0946	0.7628	0.0712	0.0274
D	0.0103	0.0515	0.2927	0.6256	0.0200
F	-	0.0069	0.0340	0.3164	0.6428

	at t = 0.70 T				
	A	B	C	D	F
A	0.7940	0.1398	0.0663	-	-
B	0.0618	0.7940	0.1310	0.0133	-
C	0.0386	0.0845	0.7940	0.0618	0.0212
D	0.0080	0.0398	0.2443	0.6880	0.0200
F	-	0.0053	0.0286	0.2649	0.7013

	at t = 0.75 T				
	A	B	C	D	F
A	0.8220	0.1293	0.0488	-	-
B	0.0534	0.8220	0.1149	0.0098	-
C	0.0337	0.0754	0.8220	0.0534	0.0156
D	0.0059	0.0293	0.2009	0.7440	0.0200
F	-	0.0039	0.0237	0.2187	0.7538

	at t = 0.80 T				
	A	B	C	D	F
A	0.8480	0.1195	0.0325	-	-
B	0.0456	0.8480	0.0999	0.0065	-
C	0.0291	0.0669	0.8480	0.0456	0.0104
D	0.0039	0.0195	0.1606	0.7960	0.0200
F	-	0.0026	0.0191	0.1758	0.8025

	at t = 0.85 T				
	A	B	C	D	F
A	0.8688	0.1117	0.0195	-	-
B	0.0394	0.8688	0.0879	0.0039	-
C	0.0255	0.0601	0.8688	0.0394	0.0062
D	0.0023	0.0117	0.1284	0.8376	0.0200
F	-	0.0016	0.0155	0.1415	0.8415

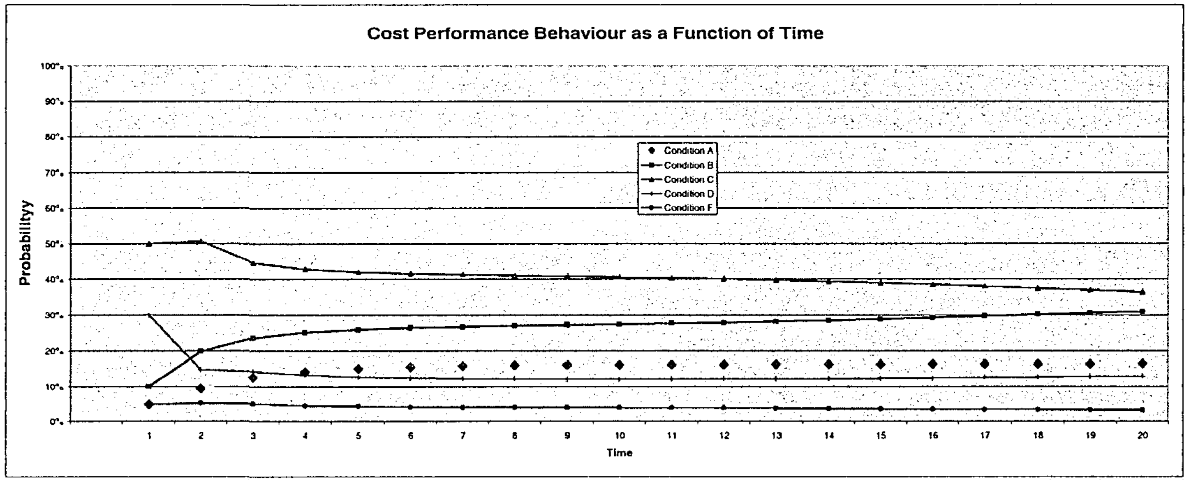
	at t = 0.90 T				
	A	B	C	D	F
A	0.8828	0.1065	0.0108	-	-
B	0.0352	0.8828	0.0799	0.0022	-
C	0.0230	0.0556	0.8828	0.0352	0.0034
D	0.0013	0.0064	0.1067	0.8656	0.0200
F	-	0.0009	0.0130	0.1184	0.8678

	at t = 0.95 T				
	A	B	C	D	F
A	0.8948	0.1020	0.0033	-	-
B	0.0316	0.8948	0.0730	0.0006	-
C	0.0209	0.0517	0.8948	0.0316	0.0010
D	0.0004	0.0020	0.0881	0.8896	0.0200
F	-	0.0003	0.0109	0.0986	0.8903

	at t = 1.00 T				
	A	B	C	D	F
A	**0.9000**	**0.1000**	-	-	-
B	**0.0300**	**0.9000**	**0.0700**	-	-
C	**0.0200**	**0.0500**	**0.9000**	**0.0300**	-
D	-	-	**0.0800**	**0.9000**	**0.0200**
F	-	-	**0.0100**	**0.0900**	**0.9000**

Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Cost Index	Expected Value	The expected cost performance at the end of the project given the latest actual status is equal to :
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00 T			
CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probat	State Proba	State Proba	State Proba	State Probs	State Proba	State Probs	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	CPI	CPI	
A		5%	9.40%	12.52%	14.11%	14.98%	15.47%	15.75%	15.91%	16.01%	16.07%	16.12%	16.16%	16.19%	16.22%	16.24%	16.27%	16.29%	16.32%	16.34%	16.36%	1.20	0.20	
B		10%	19.85%	23.57%	25.13%	25.92%	26.37%	26.67%	26.89%	27.09%	27.30%	27.51%	27.77%	28.07%	28.41%	28.79%	29.21%	29.66%	30.11%	30.57%	30.99%	1.10	0.34	
C		50%	50.65%	44.61%	42.84%	42.05%	41.58%	41.26%	41.02%	40.80%	40.58%	40.35%	40.08%	39.76%	39.39%	38.97%	38.49%	37.98%	37.45%	36.91%	36.42%	1.00	0.36	
D		30%	14.75%	14.15%	13.27%	12.64%	12.31%	12.14%	12.06%	12.03%	12.02%	12.03%	12.06%	12.12%	12.19%	12.28%	12.39%	12.52%	12.66%	12.80%	12.93%	0.90	0.12	104.42%
F		5%	5.35%	5.15%	4.65%	4.40%	4.27%	4.18%	4.13%	4.08%	4.03%	3.98%	3.93%	3.87%	3.80%	3.72%	3.64%	3.55%	3.46%	3.37%	3.29%	0.80	0.03	or Within TARGET
sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	1.044	
		0.98	1.01	1.02	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04			

Initial Probability Vector obtained from company historic records



Cost Performance Behaviour as a Function of Time

Appendix (F): Cost Forecasting Update

Forecasting Project Performance using Dynamic Markov Chains

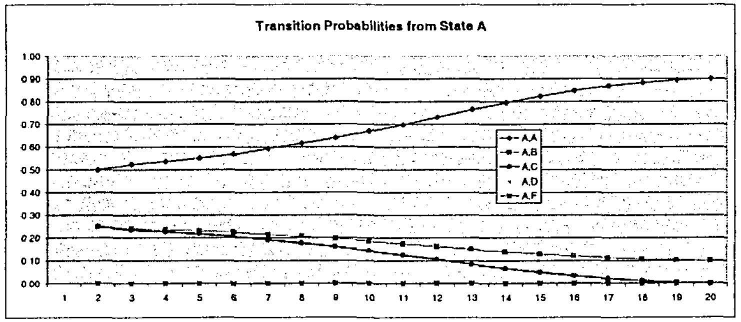
COST

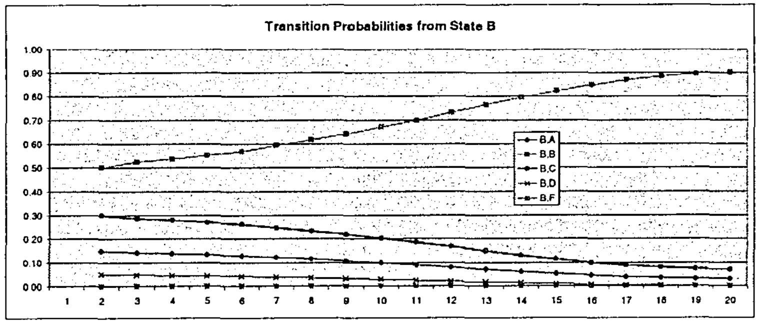
Transition Probabilities as a Function of Project Duration (T)

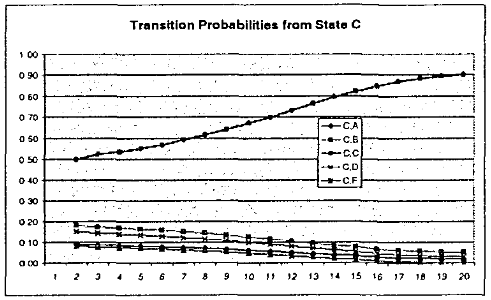
Boundary Conditions derived based on company historic database

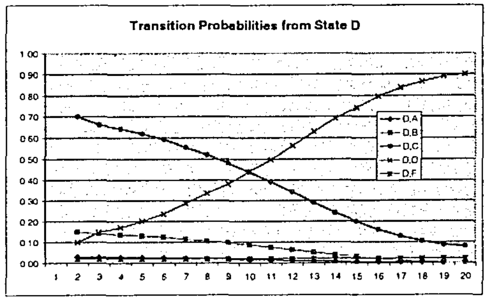
S-Curve By Cost	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)
1.50	1	at t = 0.05 T															
3.50	2	at t = 0.10 T	**0.5000**	**0.2500**	**0.2500**	-	-	**0.1500**	**0.5000**	**0.3000**	**0.0500**	-	**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**
6.00	3	at t = 0.15 T	0.5240	0.2410	0.2350	-	-	0.1428	0.5240	0.2862	0.0470	-	0.0858	0.1722	0.5240	0.1428	0.0752
9.00	4	at t = 0.20 T	0.5360	0.2365	0.2275	-	-	0.1392	0.5360	0.2793	0.0455	-	0.0837	0.1683	0.5360	0.1392	0.0728
12.80	5	at t = 0.25 T	0.5512	0.2308	0.2180	-	-	0.1346	0.5512	0.2706	0.0436	-	0.0810	0.1634	0.5512	0.1346	0.0698
17.00	6	at t = 0.30 T	*0.5680*	*0.2245*	*0.2075*	-	-	*0.1296*	*0.5680*	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664
23.46	7	at t = 0.35 T	0.5938	0.2148	0.1914	-	-	0.1218	0.5938	0.2460	0.0383	-	0.0736	0.1495	0.5938	0.1218	0.0612
29.12	8	at t = 0.40 T	0.6165	0.2063	0.1772	-	-	0.1151	0.6165	0.2330	0.0354	-	0.0696	0.1421	0.6165	0.1151	0.0567
35.20	9	at t = 0.45 T	0.6408	0.1972	0.1620	-	-	0.1078	0.6408	0.2190	0.0324	-	0.0654	0.1342	0.6408	0.1078	0.0518
42.56	10	at t = 0.50 T	0.6702	0.1862	0.1436	-	-	0.0989	0.6702	0.2021	0.0287	-	0.0602	0.1247	0.6702	0.0989	0.0460
49.70	11	at t = 0.55 T	0.6988	0.1755	0.1258	-	-	0.0904	0.6988	0.1857	0.0252	-	0.0552	0.1154	0.6988	0.0904	0.0402
57.93	12	at t = 0.60 T	0.7317	0.1631	0.1052	-	-	0.0805	0.7317	0.1668	0.0210	-	0.0494	0.1047	0.7317	0.0805	0.0337
66.20	13	at t = 0.65 T	0.7648	0.1507	0.0845	-	-	0.0706	0.7648	0.1477	0.0169	-	0.0437	0.0939	0.7648	0.0706	0.0270
73.85	14	at t = 0.70 T	0.7954	0.1392	0.0654	-	-	0.0614	0.7954	0.1301	0.0131	-	0.0383	0.0840	0.7954	0.0614	0.0209
80.50	15	at t = 0.75 T	0.8220	0.1293	0.0488	-	-	0.0534	0.8220	0.1149	0.0098	-	0.0337	0.0754	0.8220	*0.0534*	*0.0156*
87.00	16	at t = 0.80 T	0.8480	0.1195	0.0325	-	-	0.0456	0.8480	0.0999	0.0065	-	0.0291	0.0669	0.8480	0.0456	0.0104
92.20	17	at t = 0.85 T	0.8688	0.1117	0.0195	-	-	0.0394	0.8688	0.0879	0.0039	-	0.0255	0.0601	0.8688	0.0394	0.0062
95.70	18	at t = 0.90 T	0.8828	0.1065	0.0108	-	-	0.0352	0.8828	0.0799	0.0022	-	0.0230	0.0556	0.8828	0.0352	0.0034
98.70	19	at t = 0.95 T	0.8948	0.1020	0.0033	-	-	0.0316	0.8948	0.0730	0.0006	-	0.0209	0.0517	0.8948	0.0316	0.0010
100.00	20	at t = 1.00 T	**0.9000**	**0.1000**	-	-	-	**0.0300**	**0.9000**	**0.0700**	-	-	**0.0200**	**0.0500**	**0.9000**	**0.0300**	-

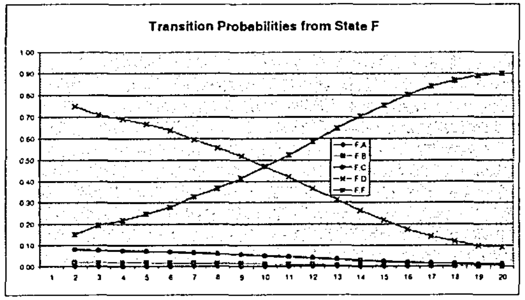
S-Curve By Cost	Period		(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.50	1	at t = 0.05 T										
3.50	2	at t = 0.10 T	**0.0300**	**0.1500**	**0.7000**	**0.1000**	**0.0200**	-	**0.0200**	**0.0800**	**0.7500**	**0.1500**
6.00	3	at t = 0.15 T	0.0282	0.1410	0.6628	0.1480	0.0200	-	0.0188	0.0758	0.7104	0.1950
9.00	4	at t = 0.20 T	0.0273	0.1365	0.6442	0.1720	0.0200	-	0.0182	0.0737	0.6906	0.2175
12.80	5	at t = 0.25 T	0.0262	0.1308	0.6206	0.2024	0.0200	-	0.0174	0.0710	0.6655	0.2460
17.00	6	at t = 0.30 T	0.0249	0.1245	0.5946	0.2360	0.0200	-	0.0166	0.0681	0.6378	0.2775
23.46	7	at t = 0.35 T	0.0230	0.1148	0.5545	0.2877	0.0200	-	0.0153	0.0636	0.5952	0.3260
29.12	8	at t = 0.40 T	0.0213	0.1063	0.5195	0.3330	0.0200	-	0.0142	0.0596	0.5578	0.3684
35.20	9	at t = 0.45 T	0.0194	0.0972	0.4818	0.3816	0.0200	-	0.0130	0.0554	0.5177	0.4140
42.56	10	at t = 0.50 T	0.0172	0.0862	0.4361	0.4405	0.0200	-	0.0115	0.0502	0.4691	0.4692
49.70	11	at t = 0.55 T	0.0151	0.0755	0.3919	0.4976	0.0200	-	0.0101	0.0452	0.4220	0.5228
57.93	12	at t = 0.60 T	0.0126	0.0631	0.3408	0.5634	0.0200	-	0.0084	0.0394	0.3677	0.5845
66.20	13	at t = 0.65 T	0.0101	0.0507	0.2896	0.6296	0.0200	-	0.0068	0.0337	0.3131	0.6465
73.85	14	at t = 0.70 T	0.0078	0.0392	0.2421	0.6908	0.0200	-	0.0052	0.0283	0.2626	0.7039
80.50	15	at t = 0.75 T	*0.0059*	*0.0293*	*0.2009*	*0.7440*	*0.0200*	-	*0.0039*	*0.0237*	*0.2187*	0.7538
87.00	16	at t = 0.80 T	0.0039	0.0195	0.1606	0.7960	0.0200	-	0.0026	0.0191	0.1758	0.8025
92.20	17	at t = 0.85 T	0.0023	0.0117	0.1284	0.8376	0.0200	-	0.0016	0.0155	0.1415	0.8415
95.70	18	at t = 0.90 T	0.0013	0.0064	0.1067	0.8656	0.0200	-	0.0009	0.0130	0.1184	0.8678
98.70	19	at t = 0.95 T	0.0004	0.0020	0.0881	0.8896	0.0200	-	0.0003	0.0109	0.0986	0.8903
100.00	20	at t = 1.00 T	-	-	**0.0800**	**0.9000**	**0.0200**	-	-	**0.0100**	**0.0900**	**0.9000**


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D

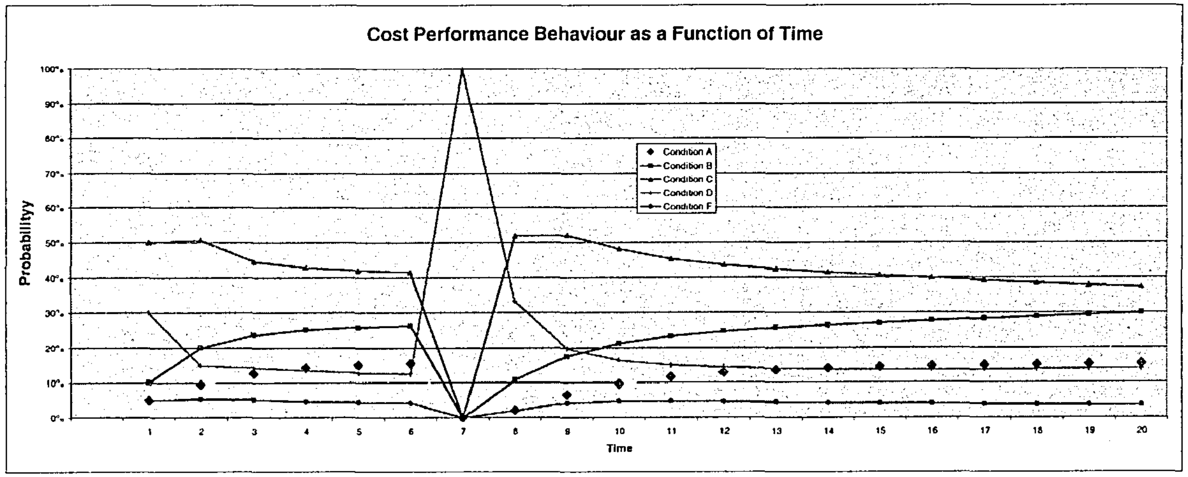

Transition Probabilities from State F

Appendix (F): Cost Forecasting Update

Forecasting Project Performance using Dynamic Markov Chains COST

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.5000**	**0.2500**	**0.2500**	-	-	0.5240	0.2410	0.2350	-	-	0.5360	0.2365	0.2275	-	-	0.5512	0.2308	0.2180	-	-
B						**0.1500**	**0.5000**	**0.3000**	**0.0500**	-	0.1428	0.5240	0.2862	0.0470	-	0.1392	0.5360	0.2793	0.0455	-	0.1346	0.5512	0.2706	0.0436	-
C						**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**	0.0858	0.1722	0.5240	0.1428	0.0752	0.0837	0.1683	0.5360	0.1392	0.0728	0.0810	0.1634	0.5512	0.1346	0.0698
D						**0.0300**	**0.1500**	**0.7000**	**0.1000**	**0.0200**	0.0282	0.1410	0.6628	0.1480	0.0200	0.0273	0.1365	0.6442	0.1720	0.0200	0.0262	0.1308	0.6206	0.2024	0.0200
F						-	**0.0200**	**0.0800**	**0.7500**	**0.1500**	-	0.0188	0.0758	0.7104	0.1950	-	0.0182	0.0737	0.6906	0.2175	-	0.0174	0.0710	0.6655	0.2460
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5680	0.2245	0.2075	-	-	0.5938	0.2148	0.1914	-	-	0.6165	0.2063	0.1772	-	-	0.6408	0.1972	0.1620	-	-	0.6702	0.1862	0.1436	-	-
B	0.1296	0.5680	0.2609	0.0415	-	0.1218	0.5938	0.2460	0.0383	-	0.1151	0.6165	0.2330	0.0354	-	0.1078	0.6408	0.2190	0.0324	-	0.0989	0.6702	0.2021	0.0287	-
C	0.0781	0.1579	0.5680	0.1296	0.0664	0.0736	0.1495	0.5938	0.1218	0.0612	0.0696	0.1421	0.6165	0.1151	0.0567	0.0654	0.1342	0.6408	0.1078	0.0518	0.0602	0.1247	0.6702	0.0989	0.0460
D	0.0249	0.1245	0.5946	0.2360	0.0200	0.0230	0.1148	0.5545	0.2877	0.0200	0.0213	0.1063	0.5195	0.3330	0.0200	0.0194	0.0972	0.4818	0.3816	0.0200	0.0172	0.0862	0.4361	0.4405	0.0200
F	-	0.0166	0.0681	0.6378	0.2775	-	0.0153	0.0636	0.5952	0.3260	-	0.0142	0.0596	0.5578	0.3684	-	0.0130	0.0554	0.5177	0.4140	-	0.0115	0.0502	0.4691	0.4692
	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6988	0.1755	0.1258	-	-	0.7317	0.1631	0.1052	-	-	0.7648	0.1507	0.0845	-	-	0.7954	0.1392	0.0654	-	-	0.8220	0.1293	0.0488	-	-
B	0.0904	0.6988	0.1857	0.0252	-	0.0805	0.7317	0.1668	0.0210	-	0.0706	0.7648	0.1477	0.0169	-	0.0614	0.7954	0.1301	0.0131	-	0.0534	0.8220	0.1149	0.0098	-
C	0.0552	0.1154	0.6988	0.0904	0.0402	0.0494	0.1047	0.7317	0.0805	0.0337	0.0437	0.0939	0.7648	0.0706	0.0270	0.0383	0.0840	0.7954	0.0614	0.0209	0.0337	0.0754	0.8220	0.0534	0.0156
D	0.0151	0.0755	0.3919	0.4976	0.0200	0.0126	0.0631	0.3408	0.5634	0.0200	0.0101	0.0507	0.2896	0.6296	0.0200	0.0078	0.0392	0.2421	0.6908	0.0200	0.0059	0.0293	0.2009	0.7440	0.0200
F	-	0.0101	0.0452	0.4220	0.5228	-	0.0084	0.0394	0.3677	0.5845	-	0.0068	0.0337	0.3131	0.6465	-	0.0052	0.0283	0.2626	0.7039	-	0.0039	0.0237	0.2187	0.7538
	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8480	0.1195	0.0325	-	-	0.8688	0.1117	0.0195	-	-	0.8828	0.1065	0.0108	-	-	0.8948	0.1020	0.0033	-	-	**0.9000**	**0.1000**	-	-	-
B	0.0456	0.8480	0.0999	0.0065	-	0.0394	0.8688	0.0879	0.0039	-	0.0352	0.8828	0.0799	0.0022	-	0.0316	0.8948	0.0730	0.0006	-	**0.0300**	**0.9000**	**0.0700**	-	-
C	0.0291	0.0669	0.8480	0.0456	0.0104	0.0255	0.0601	0.8688	0.0394	0.0062	0.0230	0.0556	0.8828	0.0352	0.0034	0.0209	0.0517	0.8948	0.0316	0.0010	**0.0200**	**0.0500**	**0.9000**	**0.0300**	-
D	0.0039	0.0195	0.1606	0.7960	0.0200	0.0023	0.0117	0.1284	0.8376	0.0200	0.0013	0.0064	0.1067	0.8656	0.0200	0.0004	0.0020	0.0881	0.8896	0.0200	-	-	**0.0800**	**0.9000**	**0.0200**
F	-	0.0026	0.0191	0.1758	0.8025	-	0.0016	0.0155	0.1415	0.8415	-	0.0009	0.0130	0.1184	0.8678	-	0.0003	0.0109	0.0986	0.8903	-	-	**0.0100**	**0.0900**	**0.9000**

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Cost Index	Expected Value	The expected cost performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80	at t = 0.85	at t = 0.90	at t = 0.95	at t = 1.00 T			
	CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probab	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Pro	State Pro	State Pro	State Pro	State Proba	CPI	CPI	
	A		5%	9.40%	12.52%	14.11%	14.98%	15.47%	0.00%	2.13%	6.55%	9.60%	11.52%	12.74%	13.54%	14.08%	14.46%	14.73%	14.94%	15.10%	15.23%	15.35%	1.20	0.18	
	B		10%	19.85%	23.57%	25.13%	25.92%	26.37%	0.00%	10.63%	17.47%	21.17%	23.31%	24.68%	25.65%	26.42%	27.08%	27.69%	28.27%	28.82%	29.35%	29.83%	1.10	0.33	
Initial Probability Vector obtained from company historic records	C		50%	50.65%	44.61%	42.84%	42.05%	41.58%	0.00%	51.95%	52.11%	48.19%	45.41%	43.63%	42.40%	41.46%	40.66%	39.93%	39.22%	38.55%	37.90%	37.31%	1.00	0.37	
	D		30%	14.75%	14.15%	13.27%	12.64%	12.31%	100.00%	33.30%	19.68%	16.29%	15.00%	14.34%	13.97%	13.75%	13.64%	13.62%	13.66%	13.73%	13.82%	13.91%	0.90	0.13	103.94%
	F		5%	5.35%	5.15%	4.65%	4.40%	4.27%	0.00%	2.00%	4.19%	4.75%	4.75%	4.60%	4.44%	4.29%	4.16%	4.03%	3.92%	3.81%	3.70%	3.61%	0.80	0.03	or Within TARGET
	sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	1.039	
			0.98	1.01	1.02	1.03	1.03	1.04		0.98	1.00	1.01	1.02	1.03	1.03	1.03	1.03	1.035	1.037	1.038	1.039	1.0394			


Cost Performance Behaviour as a Function of Time

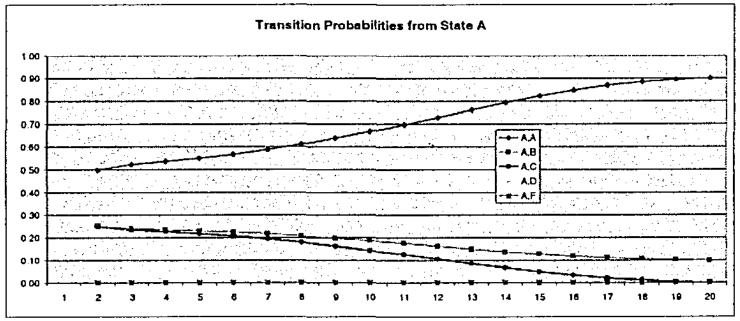
Appendix (G): Cost Forecasting Update - Scenario 1

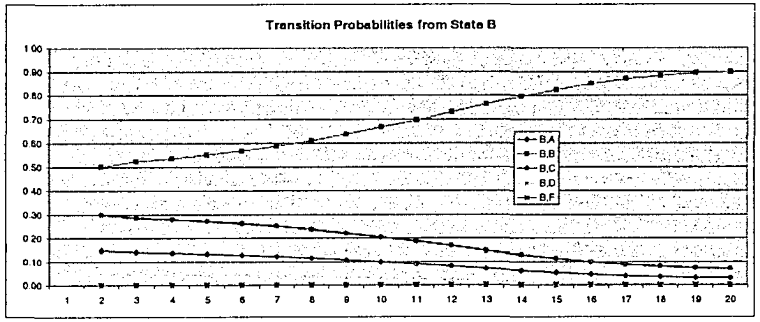
Forecasting Project Performance using Dynamic Markov Chains COST

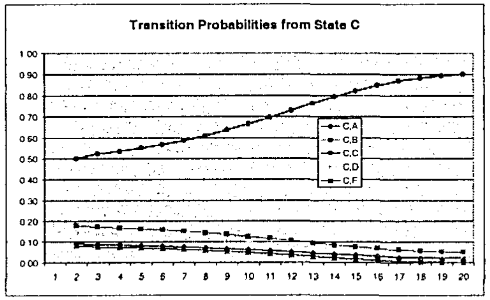
Transition Probabilities as a Function of Project Duration (T)

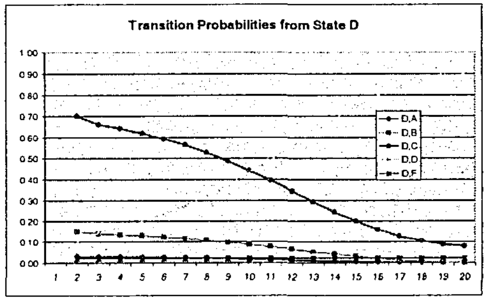
derived based on company historic database

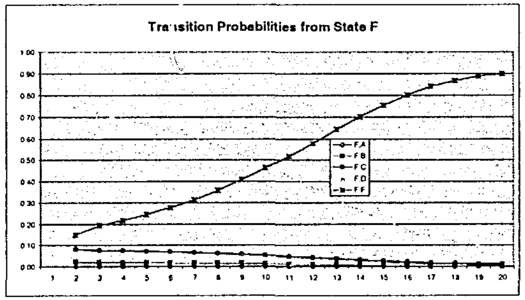
S-Curve By Cost	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.50	1	at t = 0.05 T																									
3.50	2	at t = 0.10 T	0.5000	0.2500	0.2500	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1800	0.5000	0.1500	0.0800	0.0300	0.1500	0.7000	0.1000	0.0200	-	0.0200	0.0800	0.7500	0.1500
6.00	3	at t = 0.15 T	0.5240	0.2410	0.2350	-	-	0.1428	0.5240	0.2862	0.0470	-	0.0858	0.1722	0.5240	0.1428	0.0752	0.0282	0.1410	0.6628	0.1480	0.0200	-	0.0188	0.0758	0.7104	0.1950
9.00	4	at t = 0.20 T	0.5360	0.2365	0.2275	-	-	0.1392	0.5360	0.2793	0.0455	-	0.0837	0.1683	0.5360	0.1392	0.0728	0.0273	0.1365	0.6442	0.1720	0.0200	-	0.0182	0.0737	0.6906	0.2175
12.80	5	at t = 0.25 T	0.5512	0.2308	0.2180	-	-	0.1346	0.5512	0.2706	0.0436	-	0.0810	0.1634	0.5512	0.1346	0.0698	0.0262	0.1308	0.6206	0.2024	0.0200	-	0.0174	0.0710	0.6655	0.2460
17.00	6	at t = 0.30 T	0.5680	0.2245	0.2075	-	-	0.1296	0.5680	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664	0.0249	0.1245	0.5946	0.2360	0.0200	-	0.0166	0.0681	0.6378	0.2775
21.80	7	at t = 0.35 T	0.5872	0.2173	0.1955	-	-	0.1238	0.5872	0.2499	0.0391	-	0.0747	0.1517	0.5872	0.1238	0.0626	0.0235	0.1173	0.5648	0.2744	0.0200	-	0.0156	0.0647	0.6061	0.3135
27.80	8	at t = 0.40 T	0.6112	0.2083	0.1805	-	-	0.1166	0.6112	0.2361	0.0361	-	0.0705	0.1439	0.6112	0.1166	0.0578	0.0217	0.1083	0.5276	0.3224	0.0200	-	0.0144	0.0605	0.5665	0.3585
34.60	9	at t = 0.45 T	0.6384	0.1981	0.1635	-	-	0.1085	0.6384	0.2204	0.0327	-	0.0658	0.1350	0.6384	0.1085	0.0523	0.0196	0.0981	0.4855	0.3768	0.0200	-	0.0131	0.0558	0.5216	0.4095
41.70	10	at t = 0.50 T	0.6668	0.1875	0.1458	-	-	0.1000	0.6668	0.2041	0.0292	-	0.0608	0.1258	0.6668	0.1000	0.0466	0.0175	0.0875	0.4415	0.4336	0.0200	-	0.0117	0.0508	0.4748	0.4628
48.90	11	at t = 0.55 T	0.6956	0.1767	0.1278	-	-	0.0913	0.6956	0.1875	0.0256	-	0.0558	0.1164	0.6956	0.0913	0.0409	0.0153	0.0767	0.3968	0.4912	0.0200	-	0.0102	0.0458	0.4273	0.5168
57.20	12	at t = 0.60 T	0.7288	0.1642	0.1070	-	-	0.0814	0.7288	0.1684	0.0214	-	0.0500	0.1056	0.7288	0.0814	0.0342	0.0128	0.0642	0.3454	0.5576	0.0200	-	0.0086	0.0400	0.3725	0.5790
65.70	13	at t = 0.65 T	0.7628	0.1515	0.0858	-	-	0.0712	0.7628	0.1489	0.0172	-	0.0440	0.0946	0.7628	0.0712	0.0274	0.0103	0.0515	0.2927	0.6256	0.0200	-	0.0069	0.0340	0.3164	0.6428
73.50	14	at t = 0.70 T	0.7940	0.1398	0.0663	-	-	0.0618	0.7940	0.1310	0.0133	-	0.0386	0.0845	0.7940	0.0618	0.0212	0.0080	0.0398	0.2443	0.6880	0.0200	-	0.0053	0.0286	0.2649	0.7013
80.50	15	at t = 0.75 T	0.8220	0.1293	0.0488	-	-	0.0534	0.8220	0.1149	0.0098	-	0.0337	0.0754	0.8220	0.0534	0.0156	0.0059	0.0293	0.2009	0.7440	0.0200	-	0.0039	0.0237	0.2187	0.7538
87.00	16	at t = 0.80 T	0.8480	0.1195	0.0325	-	-	0.0456	0.8480	0.0999	0.0065	-	0.0291	0.0669	0.8480	0.0456	0.0104	0.0039	0.0195	0.1606	0.7960	0.0200	-	0.0026	0.0191	0.1758	0.8025
92.20	17	at t = 0.85 T	0.8688	0.1117	0.0195	-	-	0.0394	0.8688	0.0879	0.0039	-	0.0255	0.0601	0.8688	0.0394	0.0062	0.0023	0.0117	0.1284	0.8376	0.0200	-	0.0016	0.0155	0.1415	0.8415
95.70	18	at t = 0.90 T	0.8828	0.1065	0.0108	-	-	0.0352	0.8828	0.0799	0.0022	-	0.0230	0.0556	0.8828	0.0352	0.0034	0.0013	0.0064	0.1067	0.8656	0.0200	-	0.0009	0.0130	0.1184	0.8678
98.70	19	at t = 0.95 T	0.8948	0.1020	0.0033	-	-	0.0316	0.8948	0.0730	0.0006	-	0.0209	0.0517	0.8948	0.0316	0.0010	0.0004	0.0020	0.0881	0.8896	0.0200	-	0.0003	0.0109	0.0986	0.8903
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0800	0.9000	0.0200	-	-	0.0100	0.0900	0.9000











Appendix (G): Cost Forecasting Update - Scenario 1

Forecasting Project Performance using Dynamic Markov Chains

COST

	at t = 0.05 T				
	A	B	C	D	F
A					
B					
C					
D					
F					

	at t = 0.10 T				
	A	B	C	D	F
A	**0.5000**	**0.2500**	**0.2500**	-	-
B	**0.1500**	**0.5000**	**0.3000**	**0.0500**	-
C	**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**
D	**0.0300**	**0.1500**	**0.7000**	**0.1000**	**0.0200**
F	-	**0.0200**	**0.0800**	**0.7500**	**0.1500**

	at t = 0.15 T				
	A	B	C	D	F
A	0.5240	0.2410	0.2350	-	-
B	0.1428	0.5240	0.2862	0.0470	-
C	0.0858	0.1722	0.5240	0.1428	0.0752
D	0.0282	0.1410	0.6628	0.1480	0.0200
F	-	0.0188	0.0758	0.7104	0.1950

	at t = 0.20 T				
	A	B	C	D	F
A	0.5360	0.2365	0.2275	-	-
B	0.1392	0.5360	0.2793	0.0455	-
C	0.0837	0.1683	0.5360	0.1392	0.0728
D	0.0273	0.1365	0.6442	0.1720	0.0200
F	-	0.0182	0.0737	0.6906	0.2175

	at t = 0.25 T				
	A	B	C	D	F
A	0.5512	0.2308	0.2180	-	-
B	0.1346	0.5512	0.2706	0.0436	-
C	0.0810	0.1634	0.5512	0.1346	0.0698
D	0.0262	0.1308	0.6206	0.2024	0.0200
F	-	0.0174	0.0710	0.6655	0.2460

	at t = 0.30 T				
	A	B	C	D	F
A	0.5680	0.2245	0.2075	-	-
B	0.1296	0.5680	0.2609	0.0415	-
C	0.0781	0.1579	0.5680	0.1296	0.0664
D	0.0249	0.1245	0.5946	0.2360	0.0200
F	-	0.0166	0.0681	0.6378	0.2775

	at t = 0.35 T				
	A	B	C	D	F
A	0.5872	0.2173	0.1955	-	-
B	0.1238	0.5872	0.2499	0.0391	-
C	0.0747	0.1517	0.5872	0.1238	0.0626
D	0.0235	0.1173	0.5648	0.2744	0.0200
F	-	0.0156	0.0647	0.6061	0.3135

	at t = 0.40 T				
	A	B	C	D	F
A	0.6112	0.2083	0.1805	-	-
B	0.1166	0.6112	0.2361	0.0361	-
C	0.0705	0.1439	0.6112	0.1166	0.0578
D	0.0217	0.1083	0.5276	0.3224	0.0200
F	-	0.0144	0.0605	0.5665	0.3585

	at t = 0.45 T				
	A	B	C	D	F
A	0.6384	0.1981	0.1635	-	-
B	0.1085	0.6384	0.2204	0.0327	-
C	0.0658	0.1350	0.6384	0.1085	0.0523
D	0.0196	0.0981	0.4855	0.3768	0.0200
F	-	0.0131	0.0558	0.5216	0.4095

	at t = 0.50 T				
	A	B	C	D	F
A	0.6668	0.1875	0.1458	-	-
B	0.1000	0.6668	0.2041	0.0292	-
C	0.0608	0.1258	0.6668	0.1000	0.0466
D	0.0175	0.0875	0.4415	0.4336	0.0200
F	-	0.0117	0.0508	0.4748	0.4628

	at t = 0.55 T				
	A	B	C	D	F
A	0.6956	0.1767	0.1278	-	-
B	0.0913	0.6956	0.1875	0.0256	-
C	0.0558	0.1164	0.6956	0.0913	0.0409
D	0.0153	0.0767	0.3968	0.4912	0.0200
F	-	0.0102	0.0458	0.4273	0.5168

	at t = 0.60 T				
	A	B	C	D	F
A	0.7288	0.1642	0.1070	-	-
B	0.0814	0.7288	0.1684	0.0214	-
C	0.0500	0.1056	0.7288	0.0814	0.0342
D	0.0128	0.0642	0.3454	0.5576	0.0200
F	-	0.0086	0.0400	0.3725	0.5790

	at t = 0.65 T				
	A	B	C	D	F
A	0.7628	0.1515	0.0858	-	-
B	0.0712	0.7628	0.1489	0.0172	-
C	0.0440	0.0946	0.7628	0.0712	0.0274
D	0.0103	0.0515	0.2927	0.6256	0.0200
F	-	0.0069	0.0340	0.3164	0.6428

	at t = 0.70 T				
	A	B	C	D	F
A	0.7940	0.1398	0.0663	-	-
B	0.0618	0.7940	0.1310	0.0133	-
C	0.0386	0.0845	0.7940	0.0618	0.0212
D	0.0080	0.0398	0.2443	0.6880	0.0200
F	-	0.0053	0.0286	0.2649	0.7013

	at t = 0.75 T				
	A	B	C	D	F
A	0.8220	0.1293	0.0488	-	-
B	0.0534	0.8220	0.1149	0.0098	-
C	0.0337	0.0754	0.8220	0.0534	0.0156
D	0.0059	0.0293	0.2009	0.7440	0.0200
F	-	0.0039	0.0237	0.2187	0.7538

	at t = 0.80 T				
	A	B	C	D	F
A	0.8480	0.1195	0.0325	-	-
B	0.0456	0.8480	0.0999	0.0065	-
C	0.0291	0.0669	0.8480	0.0456	0.0104
D	0.0039	0.0195	0.1606	0.7960	0.0200
F	-	0.0026	0.0191	0.1758	0.8025

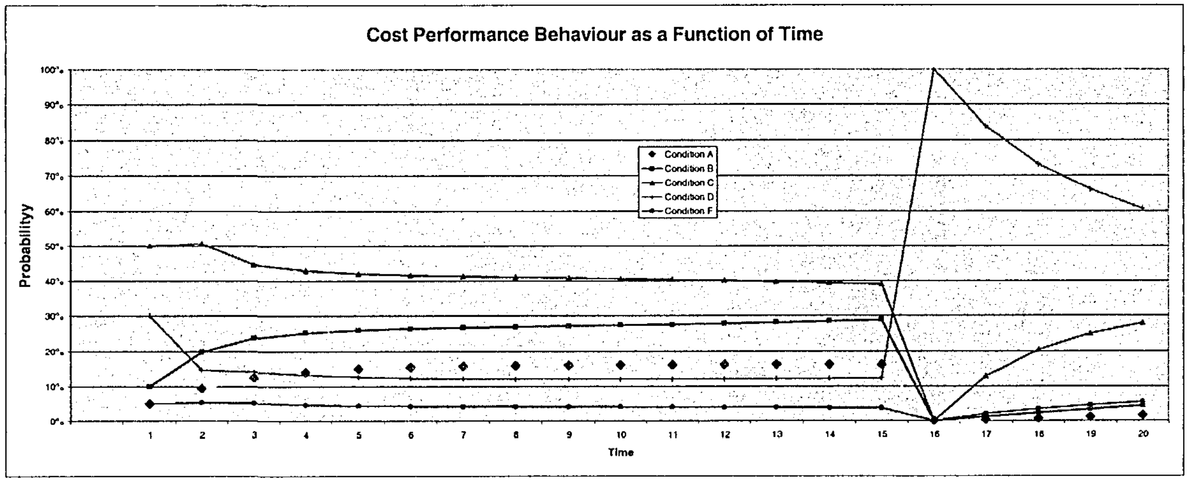
	at t = 0.85 T				
	A	B	C	D	F
A	0.8688	0.1117	0.0195	-	-
B	0.0394	0.8688	0.0879	0.0039	-
C	0.0255	0.0601	0.8688	0.0394	0.0062
D	0.0023	0.0117	0.1284	0.8376	0.0200
F	-	0.0016	0.0155	0.1415	0.8415

	at t = 0.90 T				
	A	B	C	D	F
A	0.8828	0.1065	0.0108	-	-
B	0.0352	0.8828	0.0799	0.0022	-
C	0.0230	0.0556	0.8828	0.0352	0.0034
D	0.0013	0.0064	0.1067	0.8656	0.0200
F	-	0.0009	0.0130	0.1184	0.8678

	at t = 0.95 T				
	A	B	C	D	F
A	0.8948	0.1020	0.0033	-	-
B	0.0316	0.8948	0.0730	0.0006	-
C	0.0209	0.0517	0.8948	0.0316	0.0010
D	0.0004	0.0020	0.0881	0.8896	0.0200
F	-	0.0003	0.0109	0.0986	0.8903

	at t = 1.00 T				
	A	B	C	D	F
A	**0.9000**	**0.1000**	-	-	-
B	**0.0300**	**0.9000**	**0.0700**	-	-
C	**0.0200**	**0.0500**	**0.9000**	**0.0300**	-
D	-	-	**0.0800**	**0.9000**	**0.0200**
F	-	-	**0.0100**	**0.0900**	**0.9000**

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Cost Index	Expected Value	The expected cost performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80	at t = 0.85	at t = 0.90	at t = 0.95	at t = 1.00 T			
	CONDITION		State Prob	State Proba	State Proba	State Proba	State Probabi	State Probab	State Proba	State Proba	State Proba	State Proba	State Proba	State Probe	State Proba	State Probe	State Probs	State Prot	State Prot	State Prot	State Prot	State Probs	CPI	CPI	
	A		**5%**	9.40%	12.52%	14.11%	14.98%	15.47%	15.75%	15.91%	16.01%	16.07%	16.12%	16.16%	16.19%	16.22%	16.24%	**0.00%**	0.23%	0.65%	1.11%	1.60%	1.20	0.02	
	B		**10%**	19.85%	23.57%	25.13%	25.92%	26.37%	26.67%	26.89%	27.09%	27.30%	27.51%	27.72%	28.07%	28.41%	28.79%	**0.00%**	1.17%	2.31%	3.33%	4.36%	1.10	0.05	
Initial Probability Vector obtained from company historic records	C		**50%**	50.65%	44.61%	42.84%	42.05%	41.58%	41.26%	41.02%	40.80%	40.58%	40.35%	40.08%	39.76%	39.39%	38.97%	**0.00%**	12.84%	20.39%	24.90%	27.97%	1.00	0.28	
	D		**30%**	14.75%	14.15%	13.27%	12.64%	12.31%	12.14%	12.06%	12.03%	12.02%	12.03%	12.06%	12.12%	12.19%	12.28%	**100.00%**	83.76%	73.19%	66.10%	60.65%	0.90	0.55	**93.61%**
	F		**5%**	5.35%	5.15%	4.65%	4.40%	4.27%	4.18%	4.13%	4.08%	4.03%	3.98%	3.93%	3.87%	3.80%	3.72%	**0.00%**	2.00%	3.45%	4.56%	5.43%	0.80	0.04	or Below TARGET
	sum		**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	Total	0.936	
			0.98	1.01	1.02	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	0.90	0.914	0.924	0.930	0.9361			


Cost Performance Behaviour as a Function of Time

Remarks

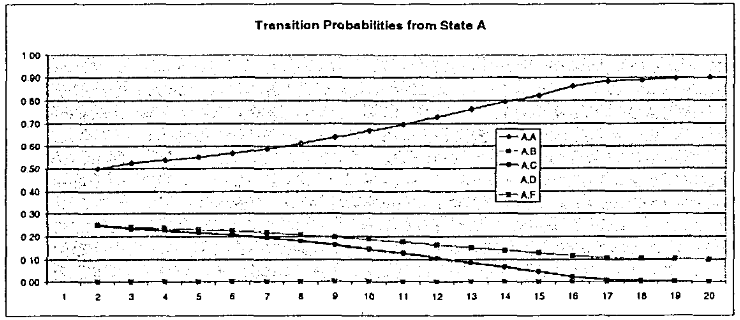
Appendix (H): Cost Forecasting Update - Scenario 2

Forecasting Project Performance using Dynamic Markov Chains COST

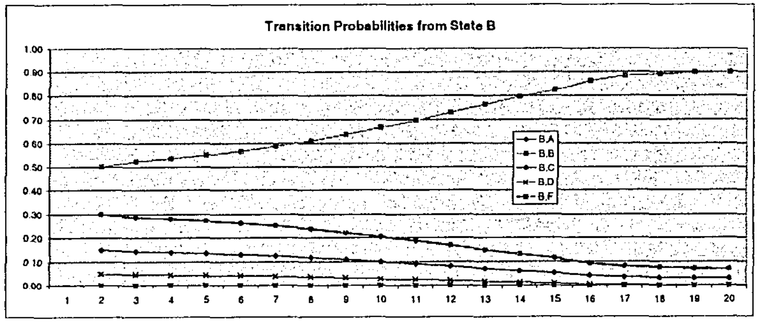
Transition Probabilities as a Function of Project Duration (T)

derived based on company historic database

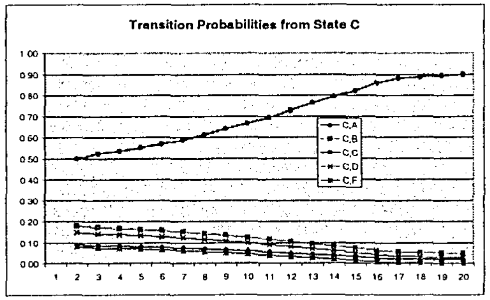
S-Curve By Cost	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.50	1	at t = 0.05 T																									
3.50	2	at t = 0.10 T	0.5000	0.2500	0.2500	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1800	0.5000	0.1500	0.0800	0.0300	0.1500	0.7000	0.1000	0.0200	-	0.0200	0.0800	0.7500	0.1500
6.00	3	at t = 0.15 T	0.5240	0.2410	0.2350	-	-	0.1428	0.5240	0.2862	0.0470	-	0.0858	0.1722	0.5240	0.1428	0.0752	0.0282	0.1410	0.6628	0.1480	0.0200	-	0.0188	0.0758	0.7104	0.1950
9.00	4	at t = 0.20 T	0.5360	0.2365	0.2275	-	-	0.1392	0.5360	0.2793	0.0455	-	0.0837	0.1683	0.5360	0.1392	0.0728	0.0273	0.1365	0.6442	0.1720	0.0200	-	0.0182	0.0737	0.6906	0.2175
12.80	5	at t = 0.25 T	0.5512	0.2308	0.2180	-	-	0.1346	0.5512	0.2706	0.0436	-	0.0810	0.1634	0.5512	0.1346	0.0698	0.0262	0.1308	0.6206	0.2024	0.0200	-	0.0174	0.0710	0.6655	0.2460
17.00	6	at t = 0.30 T	0.5680	0.2245	0.2075	-	-	0.1296	0.5680	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664	0.0249	0.1245	0.5946	0.2360	0.0200	-	0.0166	0.0681	0.6378	0.2775
21.80	7	at t = 0.35 T	0.5872	0.2173	0.1955	-	-	0.1238	0.5872	0.2499	0.0391	-	0.0747	0.1517	0.5872	0.1238	0.0626	0.0235	0.1173	0.5648	0.2744	0.0200	-	0.0156	0.0647	0.6061	0.3135
27.80	8	at t = 0.40 T	0.6112	0.2083	0.1805	-	-	0.1166	0.6112	0.2361	0.0361	-	0.0705	0.1439	0.6112	0.1166	0.0578	0.0217	0.1083	0.5276	0.3224	0.0200	-	0.0144	0.0605	0.5665	0.3585
34.60	9	at t = 0.45 T	0.6384	0.1981	0.1635	-	-	0.1085	0.6384	0.2204	0.0327	-	0.0658	0.1350	0.6384	0.1085	0.0523	0.0196	0.0981	0.4855	0.3768	0.0200	-	0.0131	0.0558	0.5216	0.4095
41.70	10	at t = 0.50 T	0.6668	0.1875	0.1458	-	-	0.1000	0.6668	0.2041	0.0292	-	0.0608	0.1258	0.6668	0.1000	0.0466	0.0175	0.0875	0.4415	0.4336	0.0200	-	0.0117	0.0508	0.4748	0.4628
48.90	11	at t = 0.55 T	0.6956	0.1767	0.1278	-	-	0.0913	0.6956	0.1875	0.0256	-	0.0558	0.1164	0.6956	0.0913	0.0409	0.0153	0.0767	0.3968	0.4912	0.0200	-	0.0102	0.0458	0.4273	0.5168
57.20	12	at t = 0.60 T	0.7288	0.1642	0.1070	-	-	0.0814	0.7288	0.1684	0.0214	-	0.0500	0.1056	0.7288	0.0814	0.0342	0.0128	0.0642	0.3454	0.5576	0.0200	-	0.0086	0.0400	0.3725	0.5790
65.70	13	at t = 0.65 T	0.7628	0.1515	0.0858	-	-	0.0712	0.7628	0.1489	0.0172	-	0.0440	0.0946	0.7628	0.0712	0.0274	0.0103	0.0515	0.2927	0.6256	0.0200	-	0.0069	0.0340	0.3164	0.6428
73.50	14	at t = 0.70 T	0.7940	0.1398	0.0663	-	-	0.0618	0.7940	0.1310	0.0133	-	0.0386	0.0845	0.7940	0.0618	0.0212	0.0080	0.0398	0.2443	0.6880	0.0200	-	0.0053	0.0286	0.2649	0.7013
80.50	15	at t = 0.75 T	0.8220	0.1293	0.0488	-	-	0.0534	0.8220	0.1149	0.0098	-	0.0337	0.0754	0.8220	0.0534	0.0156	0.0059	0.0293	0.2009	0.7440	0.0200	-	0.0039	0.0237	0.2187	0.7538
90.20	16	at t = 0.80 T	0.8608	0.1147	0.0245	-	-	0.0418	0.8608	0.0925	0.0049	-	0.0269	0.0627	0.8608	0.0418	0.0078	0.0029	0.0147	0.1408	0.8216	0.0200	-	0.0020	0.0169	0.1547	0.8265
95.80	17	at t = 0.85 T	0.8832	0.1063	0.0105	-	-	0.0350	0.8832	0.0797	0.0021	-	0.0229	0.0555	0.8832	0.0350	0.0034	0.0013	0.0063	0.1060	0.8664	0.0200	-	0.0008	0.0129	0.1177	0.8685
97.30	18	at t = 0.90 T	0.8892	0.1041	0.0068	-	-	0.0332	0.8892	0.0762	0.0014	-	0.0219	0.0535	0.8892	0.0332	0.0022	0.0008	0.0041	0.0967	0.8784	0.0200	-	0.0005	0.0119	0.1078	0.8798
99.15	19	at t = 0.95 T	0.8966	0.1013	0.0021	-	-	0.0310	0.8966	0.0720	0.0004	-	0.0206	0.0511	0.8966	0.0310	0.0007	0.0003	0.0013	0.0853	0.8932	0.0200	-	0.0002	0.0106	0.0956	0.8936
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0800	0.9000	0.0200	-	-	0.0100	0.0900	0.9000



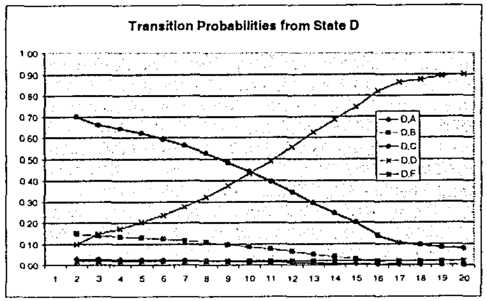
Transition Probabilities from State A



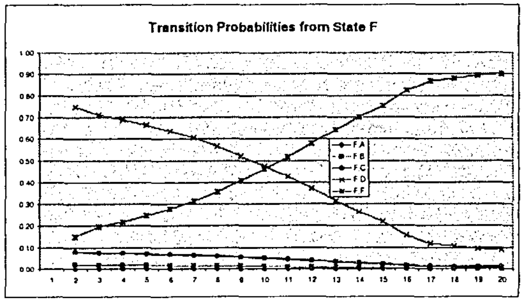
Transition Probabilities from State B



Transition Probabilities from State C



Transition Probabilities from State D



Transition Probabilities from State F

Appendix (H): Cost Forecasting Update - Scenario 2

Forecasting Project Performance using Dynamic Markov Chains

COST

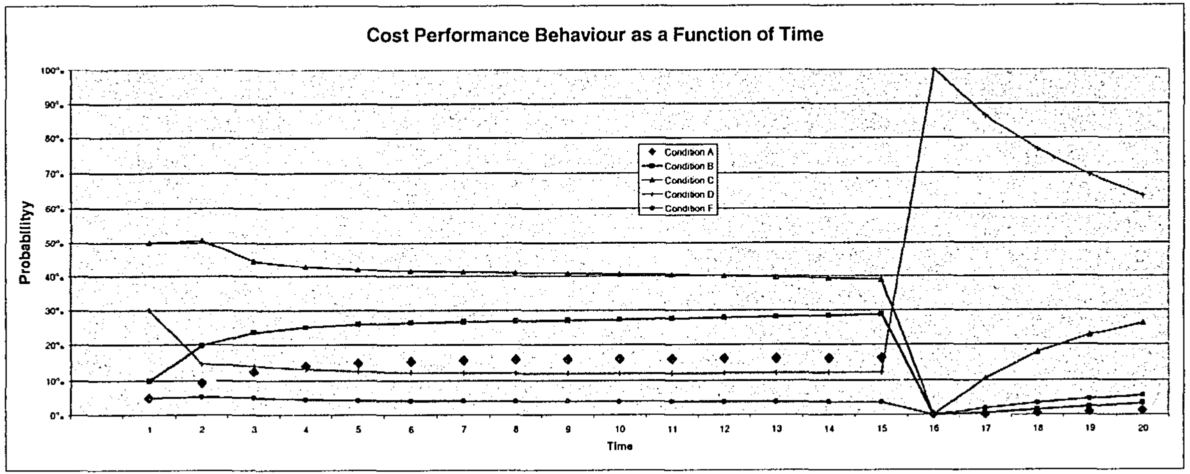
	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.5000**	**0.2500**	**0.2500**	-	-	0.5240	0.2410	0.2350	-	-	0.5360	0.2365	0.2275	-	-	0.5512	0.2308	0.2180	-	-
B						**0.1500**	**0.5000**	**0.3000**	**0.0500**	-	0.1428	0.5240	0.2862	0.0470	-	0.1392	0.5360	0.2793	0.0455	-	0.1346	0.5512	0.2706	0.0436	-
C						**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**	0.0858	0.1722	0.5240	0.1428	0.0752	0.0837	0.1683	0.5360	0.1392	0.0728	0.0810	0.1634	0.5512	0.1346	0.0698
D						**0.0300**	**0.1500**	**0.7000**	**0.1000**	**0.0200**	0.0282	0.1410	0.6628	0.1480	0.0200	0.0273	0.1365	0.6442	0.1720	0.0200	0.0262	0.1308	0.6206	0.2024	0.0200
F						-	**0.0200**	**0.0800**	**0.7500**	**0.1500**	-	0.0188	0.0758	0.7104	0.1950	-	0.0182	0.0737	0.6906	0.2175	-	0.0174	0.0710	0.6655	0.2460

	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5680	0.2245	0.2075	-	-	0.5872	0.2173	0.1955	-	-	0.6112	0.2083	0.1805	-	-	0.6384	0.1981	0.1635	-	-	0.6668	0.1875	0.1458	-	-
B	0.1296	0.5680	0.2609	0.0415	-	0.1238	0.5872	0.2499	0.0391	-	0.1166	0.6112	0.2361	0.0361	-	0.1085	0.6384	0.2204	0.0327	-	0.1000	0.6668	0.2041	0.0292	-
C	0.0781	0.1579	0.5680	0.1296	0.0664	0.0747	0.1517	0.5872	0.1238	0.0626	0.0705	0.1439	0.6112	0.1166	0.0578	0.0658	0.1350	0.6384	0.1085	0.0523	0.0608	0.1258	0.6668	0.1000	0.0466
D	0.0249	0.1245	0.5946	0.2360	0.0200	0.0235	0.1173	0.5648	0.2744	0.0200	0.0217	0.1083	0.5276	0.3224	0.0200	0.0196	0.0981	0.4855	0.3768	0.0200	0.0175	0.0875	0.4415	0.4336	0.0200
F	-	0.0166	0.0681	0.6378	0.2775	-	0.0156	0.0647	0.6061	0.3135	-	0.0144	0.0605	0.5665	0.3585	-	0.0131	0.0558	0.5216	0.4095	-	0.0117	0.0508	0.4748	0.4628

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6956	0.1767	0.1278	-	-	0.7288	0.1642	0.1070	-	-	0.7628	0.1515	0.0858	-	-	0.7940	0.1398	0.0663	-	-	0.8220	0.1293	0.0488	-	-
B	0.0913	0.6956	0.1875	0.0256	-	0.0814	0.7288	0.1684	0.0214	-	0.0712	0.7628	0.1489	0.0172	-	0.0618	0.7940	0.1310	0.0133	-	0.0534	0.8220	0.1149	0.0098	-
C	0.0558	0.1164	0.6956	0.0913	0.0409	0.0500	0.1056	0.7288	0.0814	0.0342	0.0440	0.0946	0.7628	0.0712	0.0274	0.0386	0.0845	0.7940	0.0618	0.0212	0.0337	0.0754	0.8220	0.0534	0.0156
D	0.0153	0.0767	0.3968	0.4912	0.0200	0.0128	0.0642	0.3454	0.5576	0.0200	0.0103	0.0515	0.2927	0.6256	0.0200	0.0080	0.0398	0.2443	0.6880	0.0200	0.0059	0.0293	0.2009	0.7440	0.0200
F	-	0.0102	0.0458	0.4273	0.5168	-	0.0086	0.0400	0.3725	0.5790	-	0.0069	0.0340	0.3164	0.6428	-	0.0053	0.0286	0.2649	0.7013	-	0.0039	0.0237	0.2187	0.7538

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8608	0.1147	0.0245	-	-	0.8832	0.1063	0.0105	-	-	0.8892	0.1041	0.0068	-	-	0.8966	0.1013	0.0021	-	-	**0.9000**	**0.1000**	-	-	-
B	0.0418	0.8608	0.0925	0.0049	-	0.0350	0.8832	0.0797	0.0021	-	0.0332	0.8892	0.0762	0.0014	-	0.0310	0.8966	0.0720	0.0004	-	**0.0300**	**0.9000**	**0.0700**	-	-
C	0.0269	0.0627	0.8608	0.0418	0.0078	0.0229	0.0555	0.8832	0.0350	0.0034	0.0219	0.0535	0.8892	0.0332	0.0022	0.0206	0.0511	0.8966	0.0310	0.0007	**0.0200**	**0.0500**	**0.9000**	**0.0300**	-
D	0.0029	0.0147	0.1408	0.8216	0.0200	0.0013	0.0063	0.1060	0.8664	0.0200	0.0008	0.0041	0.0967	0.8784	0.0200	0.0003	0.0013	0.0853	0.8932	0.0200	-	-	**0.0800**	**0.9000**	**0.0200**
F	-	0.0020	0.0169	0.1547	0.8265	-	0.0008	0.0129	0.1177	0.8685	-	0.0005	0.0119	0.1078	0.8798	-	0.0002	0.0106	0.0956	0.8936	-	-	**0.0100**	**0.0900**	**0.9000**

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Cost Index	Expected Value	The expected cost performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80 T	at t = 0.85 T	at t = 0.90 T	at t = 0.95 T	at t = 1.00 T			
	CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probab	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prob	State Prob	State Prob	State Prob	State Proba	CPI	CPI	
	A		5%	9.40%	12.52%	14.11%	14.98%	15.47%	15.75%	15.91%	16.01%	16.07%	16.12%	16.16%	16.19%	16.22%	16.24%	0.00%	0.13%	0.44%	0.82%	1.27%	1.20	0.02	
	B		10%	19.85%	23.57%	25.13%	25.92%	26.37%	26.67%	26.89%	27.09%	27.30%	27.51%	27.77%	28.07%	28.41%	28.79%	0.00%	0.63%	1.49%	2.39%	3.37%	1.10	0.04	
Initial Probability Vector obtained from company historic records	C		50%	50.65%	44.61%	42.84%	42.05%	41.58%	41.26%	41.02%	40.80%	40.58%	40.35%	40.08%	39.76%	39.39%	38.97%	0.00%	10.60%	17.88%	22.72%	26.21%	1.00	0.26	
	D		30%	14.75%	14.15%	13.27%	12.64%	12.31%	12.14%	12.06%	12.03%	12.02%	12.03%	12.06%	12.12%	12.19%	12.28%	100.00%	86.64%	76.67%	69.38%	63.54%	0.90	0.57	93.12%
	F		5%	5.35%	5.15%	4.65%	4.40%	4.27%	4.18%	4.13%	4.08%	4.03%	3.98%	3.93%	3.87%	3.80%	3.72%	0.00%	2.00%	3.52%	4.69%	5.61%	0.80	0.04	or Below TARGET
	sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	0.931	
			0.98	1.01	1.02	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	0.90	0.910	0.919	0.925	0.9312			


Cost Performance Behaviour as a Function of Time

Appendix (I): Cost Forecasting Update - Scenario 3

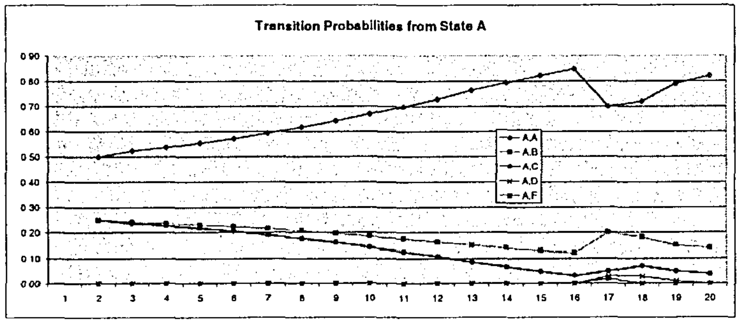
Forecasting Project Performance using Dynamic Markov Chains

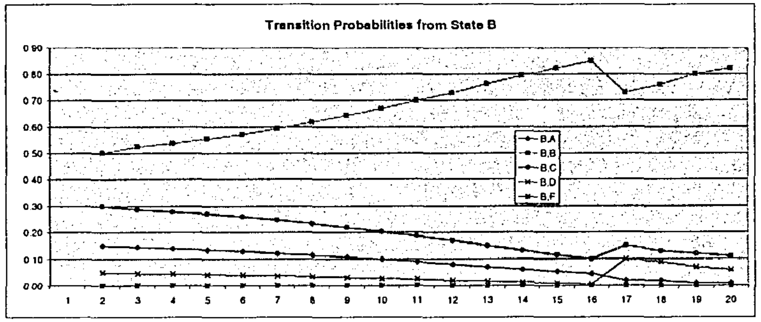
COST

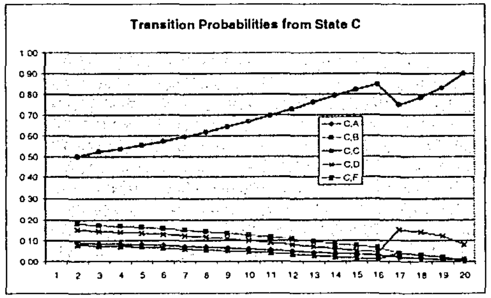
Transition Probabilities as a Function of Project Duration (T)

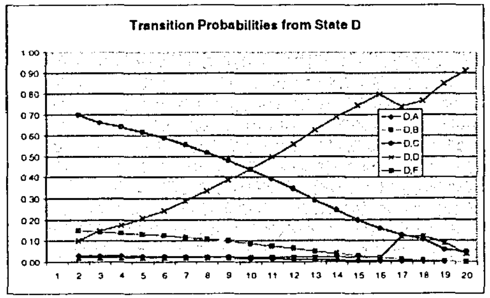
derived based on company historic database

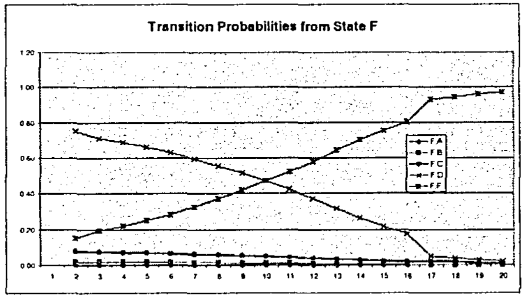
S-Curve By Cost	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.50	1	at t = 0.05 T																									
3.50	2	at t = 0.10 T	**0.5000**	**0.2500**	**0.2500**	-	-	**0.1500**	**0.5000**	**0.3000**	**0.0500**	-	**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**	**0.0300**	**0.1500**	**0.7000**	**0.1000**	**0.0200**	-	**0.0200**	**0.0800**	**0.7500**	**0.1500**
6.00	3	at t = 0.15 T	0.5240	0.2410	0.2350	-	-	0.1428	0.5240	0.2862	0.0470	-	0.0858	0.1722	0.5240	0.1428	0.0752	0.0282	0.1410	0.6628	0.1480	0.0200	-	0.0188	0.0758	0.7104	0.1950
9.00	4	at t = 0.20 T	0.5380	0.2358	0.2263	-	-	0.1386	0.5380	0.2782	0.0453	-	0.0834	0.1677	0.5380	0.1386	0.0724	0.0272	0.1358	0.6411	0.1760	0.0200	-	0.0181	0.0734	0.6873	0.2213
12.80	5	at t = 0.25 T	0.5540	0.2298	0.2163	-	-	0.1338	0.5540	0.2690	0.0433	-	0.0806	0.1625	0.5540	0.1338	0.0692	0.0260	0.1298	0.6163	0.2080	0.0200	-	0.0173	0.0706	0.6607	0.2513
17.00	6	at t = 0.30 T	0.5720	0.2230	0.2050	-	-	0.1284	0.5720	0.2586	0.0410	-	0.0774	0.1566	0.5720	0.1284	0.0656	0.0246	0.1230	0.5884	0.2440	0.0200	-	0.0164	0.0674	0.6312	0.2850
21.80	7	at t = 0.35 T	0.5940	0.2148	0.1913	-	-	0.1218	0.5940	0.2460	0.0383	-	0.0736	0.1495	0.5940	0.1218	0.0612	0.0230	0.1148	0.5543	0.2880	0.0200	-	0.0153	0.0636	0.5949	0.3263
27.80	8	at t = 0.40 T	0.6180	0.2058	0.1763	-	-	0.1146	0.6180	0.2322	0.0353	-	0.0694	0.1417	0.6180	0.1146	0.0564	0.0212	0.1058	0.5171	0.3360	0.0200	-	0.0141	0.0594	0.5553	0.3713
34.60	9	at t = 0.45 T	0.6428	0.1965	0.1608	-	-	0.1072	0.6428	0.2179	0.0322	-	0.0650	0.1336	0.6428	0.1072	0.0514	0.0193	0.0965	0.4787	0.3856	0.0200	-	0.0129	0.0550	0.5144	0.4178
41.70	10	at t = 0.50 T	0.6700	0.1863	0.1438	-	-	0.0990	0.6700	0.2023	0.0288	-	0.0603	0.1248	0.6700	0.0990	0.0460	0.0173	0.0863	0.4365	0.4400	0.0200	-	0.0115	0.0503	0.4695	0.4688
48.90	11	at t = 0.55 T	0.6988	0.1755	0.1258	-	-	0.0904	0.6988	0.1857	0.0252	-	0.0552	0.1154	0.6988	0.0904	0.0402	0.0151	0.0755	0.3919	0.4976	0.0200	-	0.0101	0.0452	0.4220	0.5228
57.20	12	at t = 0.60 T	0.7288	0.1642	0.1070	-	-	0.0814	0.7288	0.1684	0.0214	-	0.0500	0.1056	0.7288	0.0814	0.0342	0.0128	0.0642	0.3454	0.5576	0.0200	-	0.0086	0.0400	0.3725	0.5790
65.70	13	at t = 0.65 T	0.7628	0.1515	0.0858	-	-	0.0712	0.7628	0.1489	0.0172	-	0.0440	0.0946	0.7628	0.0712	0.0274	0.0103	0.0515	0.2927	0.6256	0.0200	-	0.0069	0.0340	0.3164	0.6428
73.50	14	at t = 0.70 T	0.7940	0.1398	0.0663	-	-	0.0618	0.7940	0.1310	0.0133	-	0.0386	0.0845	0.7940	0.0618	0.0212	0.0080	0.0398	0.2443	0.6880	0.0200	-	0.0053	0.0286	0.2649	0.7013
80.50	15	at t = 0.75 T	0.8220	0.1293	0.0488	-	-	0.0534	0.8220	0.1149	0.0098	-	0.0337	0.0754	0.8220	0.0534	0.0156	0.0059	0.0293	0.2009	0.7440	0.0200	-	0.0039	0.0237	0.2187	0.7538
87.00	16	at t = 0.80 T	0.8480	0.1195	0.0325	-	-	0.0456	0.8480	0.0999	0.0065	-	0.0291	0.0669	0.8480	0.0456	0.0104	0.0039	0.0195	0.1606	0.7960	0.0200	-	0.0026	0.0191	0.1758	0.8025
92.20	17	at t = 0.85 T	**0.7000**	0.2000	0.0500	0.0300	0.0200	0.0200	**0.7300**	0.1500	0.1000	-	0.0200	0.0400	**0.7500**	0.1500	0.0400	0.0023	0.0117	0.1284	**0.7376**	0.1200	-	-	0.0200	0.0500	**0.9300**
95.70	18	at t = 0.90 T	**0.7200**	0.1800	0.0700	0.0300	-	0.0200	**0.7600**	0.1300	0.0900	-	0.0150	0.0300	**0.7850**	0.1400	0.0300	0.0013	0.0064	0.1067	**0.7656**	0.1200	-	-	0.0200	0.0400	**0.9400**
98.70	19	at t = 0.95 T	**0.7900**	0.1500	0.0500	0.0100	-	0.0100	**0.8000**	0.1200	0.0700	-	0.0100	0.0200	**0.8300**	0.1200	0.0200	0.0004	0.0020	0.0581	**0.8496**	0.0900	-	-	0.0100	0.0300	**0.9600**
100.00	*20*	*at t = 1.00 T*	***0.8200***	***0.1400***	***0.0400***	-	-	***0.0100***	***0.8200***	***0.1100***	***0.0600***	-	***0.0100***	***0.0100***	***0.9000***	***0.0800***	-	-	-	***0.0500***	***0.9100***	***0.0400***	-	-	***0.0100***	***0.0200***	***0.9700***


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

Appendix (I): Cost Forecasting Update - Scenario 3

Forecasting Project Performance using Dynamic Markov Chains COST

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						0.5000	0.2500	0.2500	-	-	0.5240	0.2410	0.2350	-	-	0.5380	0.2358	0.2263	-	-	0.5540	0.2298	0.2163	-	-
B						0.1500	0.5000	0.3000	0.0500	-	0.1428	0.5240	0.2862	0.0470	-	0.1386	0.5380	0.2782	0.0453	-	0.1338	0.5540	0.2690	0.0433	-
C						0.0900	0.1800	0.5000	0.1500	0.0800	0.0858	0.1722	0.5240	0.1428	0.0752	0.0834	0.1677	0.5380	0.1386	0.0724	0.0806	0.1625	0.5540	0.1338	0.0692
D						0.0300	0.1500	0.7000	0.1000	0.0200	0.0282	0.1410	0.6628	0.1480	0.0200	0.0272	0.1358	0.6411	0.1760	0.0200	0.0260	0.1298	0.6163	0.2080	0.0200
F						-	0.0200	0.0800	0.7500	0.1500	-	0.0188	0.0758	0.7104	0.1950	-	0.0181	0.0734	0.6873	0.2213	-	0.0173	0.0706	0.6609	0.2513

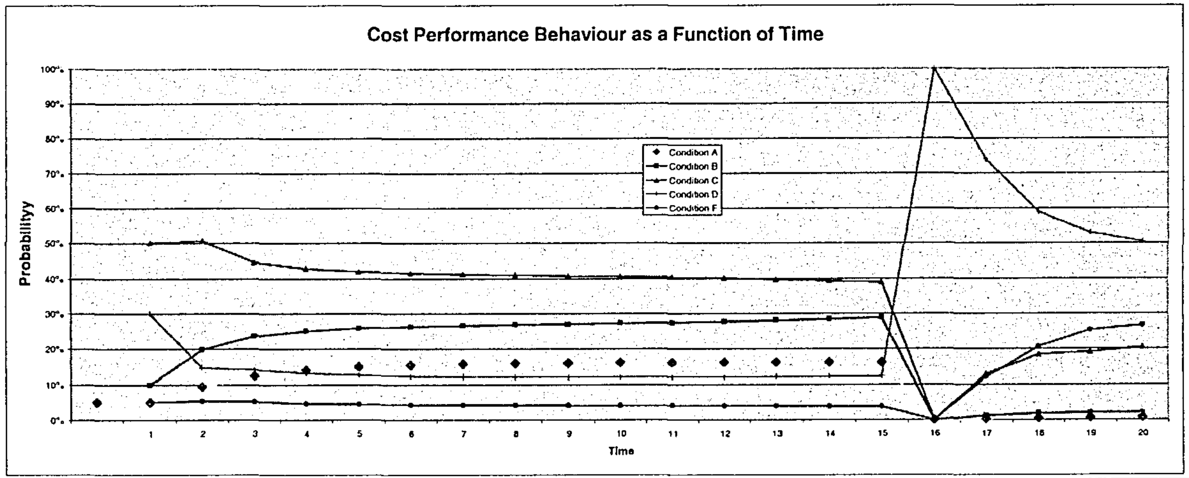
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5720	0.2230	0.2050	-	-	0.5940	0.2148	0.1913	-	-	0.6180	0.2058	0.1763	-	-	0.6428	0.1965	0.1608	-	-	0.6700	0.1863	0.1438	-	-
B	0.1284	0.5720	0.2586	0.0410	-	0.1218	0.5940	0.2460	0.0383	-	0.1146	0.6180	0.2322	0.0353	-	0.1072	0.6428	0.2179	0.0322	-	0.0990	0.6700	0.2023	0.0288	-
C	0.0774	0.1566	0.5720	0.1284	0.0656	0.0736	0.1495	0.5940	0.1218	0.0612	0.0694	0.1417	0.6180	0.1146	0.0564	0.0650	0.1336	0.6428	0.1072	0.0514	0.0603	0.1248	0.6700	0.0990	0.0460
D	0.0246	0.1230	0.5884	0.2440	0.0200	0.0230	0.1148	0.5543	0.2880	0.0200	0.0212	0.1058	0.5171	0.3360	0.0200	0.0193	0.0965	0.4787	0.3856	0.0200	0.0173	0.0863	0.4365	0.4400	0.0200
F	-	0.0164	0.0674	0.6312	0.2850	-	0.0153	0.0636	0.5949	0.3263	-	0.0141	0.0594	0.5553	0.3713	-	0.0129	0.0550	0.5144	0.4178	-	0.0115	0.0503	0.4695	0.4688

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6988	0.1755	0.1258	-	-	0.7288	0.1642	0.1070	-	-	0.7628	0.1515	0.0858	-	-	0.7940	0.1398	0.0663	-	-	0.8220	0.1293	0.0488	-	-
B	0.0904	0.6988	0.1857	0.0252	-	0.0814	0.7288	0.1684	0.0214	-	0.0712	0.7628	0.1489	0.0172	-	0.0618	0.7940	0.1310	0.0133	-	0.0534	0.8220	0.1149	0.0098	-
C	0.0552	0.1154	0.6988	0.0904	0.0402	0.0500	0.1056	0.7288	0.0814	0.0342	0.0440	0.0946	0.7628	0.0712	0.0274	0.0386	0.0845	0.7940	0.0618	0.0212	0.0337	0.0754	0.8220	0.0534	0.0156
D	0.0151	0.0755	0.3919	0.4976	0.0200	0.0128	0.0642	0.3454	0.5576	0.0200	0.0103	0.0515	0.2927	0.6256	0.0200	0.0080	0.0398	0.2443	0.6880	0.0200	0.0059	0.0293	0.2009	0.7440	0.0200
F	-	0.0101	0.0452	0.4220	0.5228	-	0.0086	0.0400	0.3725	0.5790	-	0.0069	0.0340	0.3164	0.6428	-	0.0053	0.0286	0.2649	0.7013	-	0.0039	0.0237	0.2187	0.7538

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8480	0.1195	0.0325	-	-	0.7000	0.2000	0.0500	0.0300	0.0200	0.7200	0.1800	0.0700	0.0300	-	0.7900	0.1500	0.0500	0.0100	-	0.8200	0.1400	0.0400	-	-
B	0.0456	0.8480	0.0999	0.0065	-	0.0200	0.7300	0.1500	0.1000	-	0.0200	0.7600	0.1300	0.0900	-	0.0100	0.8000	0.1200	0.0700	-	0.0100	0.8200	0.1100	0.0600	-
C	0.0291	0.0669	0.8480	0.0456	0.0104	0.0200	0.0400	0.7500	0.1500	0.0400	0.0150	0.0300	0.7850	0.1400	0.0300	0.0100	0.0200	0.8300	0.1200	0.0200	0.0100	0.0100	0.9000	0.0800	-
D	0.0039	0.0195	0.1606	0.7960	0.0200	0.0023	0.0117	0.1284	0.7376	0.1200	0.0013	0.0064	0.1067	0.7656	0.1200	0.0004	0.0020	0.0581	0.8496	0.0900	-	-	0.0500	0.9100	0.0400
F	-	0.0026	0.0191	0.1758	0.8025	-	-	0.0200	0.0500	0.9300	-	-	0.0200	0.0400	0.9400	-	-	0.0100	0.0300	0.9600	-	-	0.0100	0.0200	0.9700

Initial Probability Vector obtained from company historic records

Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Cost Index	Expected Value	The expected cost performance at the end of the project given the latest actual status is equal to :
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00 T			
CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probal	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Probs	State Proba	State Probs	State Pro	State Pro	State Pro	State Pro	State Probs	CPI	CPI	
A	5%	5%	9.40%	12.52%	14.11%	14.97%	15.46%	15.74%	15.90%	16.00%	16.07%	16.12%	16.16%	16.19%	16.22%	16.25%	0.00%	0.23%	0.48%	0.60%	0.71%	1.20	0.01	
B		10%	19.85%	23.57%	25.13%	25.92%	26.38%	26.68%	26.91%	27.12%	27.32%	27.54%	27.78%	28.08%	28.42%	28.79%	0.00%	1.17%	1.79%	1.99%	1.91%	1.10	0.02	
C		50%	50.65%	44.61%	42.84%	42.05%	41.57%	41.24%	40.99%	40.78%	40.56%	40.33%	40.07%	39.75%	39.38%	38.97%	0.00%	12.84%	18.35%	19.09%	20.33%	1.00	0.20	
D		30%	14.75%	14.15%	13.28%	12.65%	12.33%	12.16%	12.07%	12.03%	12.02%	12.03%	12.06%	12.12%	12.19%	12.28%	100.00%	73.76%	58.86%	52.96%	50.34%	0.90	0.45	89.95%
F		5%	5.35%	5.15%	4.65%	4.40%	4.27%	4.18%	4.12%	4.07%	4.03%	3.98%	3.92%	3.86%	3.79%	3.72%	0.00%	12.00%	20.52%	25.36%	26.72%	0.80	0.21	or Below TARGET
sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	0.8995	
		0.98	1.01	1.02	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	0.90	0.904	0.903	0.900	0.900			


Cost Performance Behaviour as a Function of Time

APPENDIX (J)

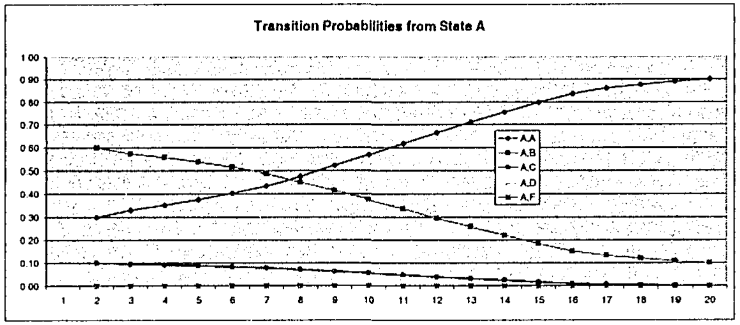
Forecasting Project Performance using Dynamic Markov Chains

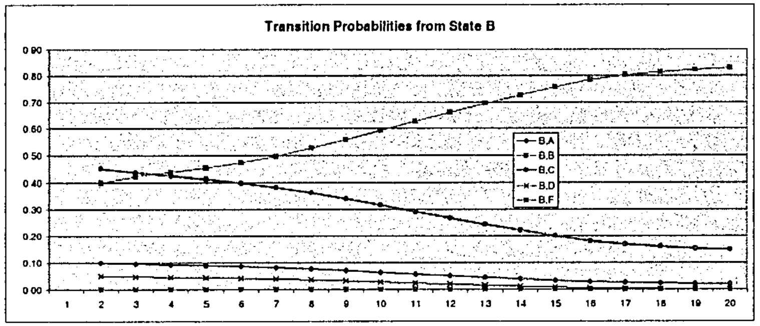
Schedule Forecasting Model

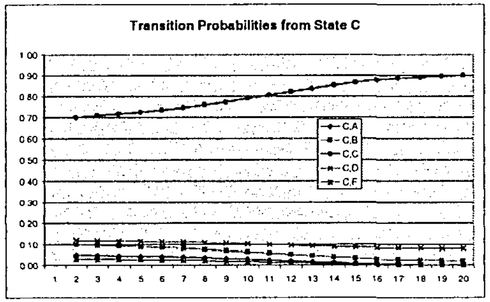
Transition Probabilities as a Function of Project Duration (T)

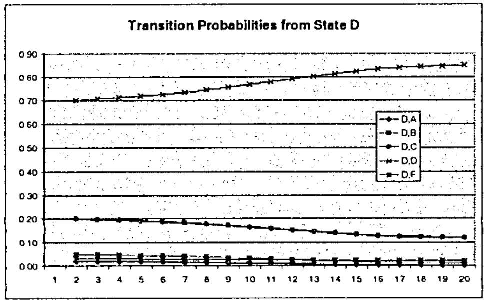
boundary conditions derived based on company historic database

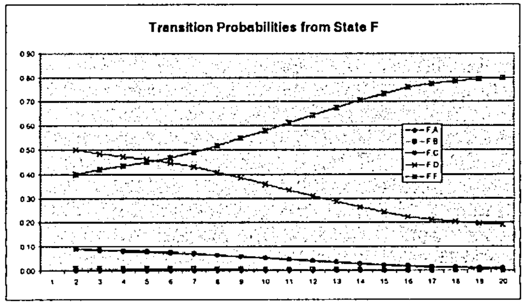
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	0.3000	0.6000	0.1000	-	-	0.1000	0.4000	0.4500	0.0500	-	0.0500	0.1000	0.7000	0.1200	0.0300	0.0200	0.0500	0.2000	0.7000	0.0300	-	0.0100	0.0900	0.5000	0.4000
5.00	3	at t = 0.15 T	0.3300	0.5750	0.0950	-	-	0.0960	0.4215	0.4350	0.0475	-	0.0475	0.0960	0.7100	0.1180	0.0285	0.0190	0.0480	0.1960	0.7075	0.0295	-	0.0095	0.0860	0.4845	0.4200
8.50	4	at t = 0.20 T	0.3510	0.5575	0.0915	-	-	0.0932	0.4366	0.4245	0.0458	-	0.0458	0.0932	0.7170	0.1166	0.0275	0.0183	0.0466	0.1932	0.7128	0.0292	-	0.0092	0.0832	0.4737	0.4340
12.50	5	at t = 0.25 T	0.3750	0.5375	0.0875	-	-	0.0900	0.4538	0.4125	0.0438	-	0.0438	0.0900	0.7250	0.1150	0.0263	0.0175	0.0450	0.1900	0.7188	0.0288	-	0.0088	0.0800	0.4613	0.4500
17.00	6	at t = 0.30 T	0.4020	0.5150	0.0830	-	-	0.0864	0.4731	0.3990	0.0415	-	0.0415	0.0864	0.7340	0.1132	0.0249	0.0166	0.0432	0.1864	0.7255	0.0283	-	0.0083	0.0764	0.4473	0.4680
22.43	7	at t = 0.35 T	0.4346	0.4879	0.0776	-	-	0.0821	0.4964	0.3827	0.0388	-	0.0388	0.0821	0.7449	0.1110	0.0233	0.0155	0.0410	0.1821	0.7336	0.0278	-	0.0078	0.0721	0.4305	0.4897
29.43	8	at t = 0.40 T	0.4766	0.4529	0.0706	-	-	0.0765	0.5265	0.3617	0.0353	-	0.0353	0.0765	0.7589	0.1082	0.0212	0.0141	0.0382	0.1765	0.7441	0.0271	-	0.0071	0.0665	0.4088	0.5177
36.93	9	at t = 0.45 T	0.5216	0.4154	0.0631	-	-	0.0705	0.5588	0.3392	0.0315	-	0.0315	0.0705	0.7739	0.1052	0.0189	0.0126	0.0352	0.1705	0.7554	0.0263	-	0.0063	0.0605	0.3855	0.5477
44.93	10	at t = 0.50 T	0.5696	0.3754	0.0551	-	-	0.0641	0.5932	0.3152	0.0275	-	0.0275	0.0641	0.7899	0.1020	0.0165	0.0110	0.0320	0.1641	0.7674	0.0255	-	0.0055	0.0541	0.3607	0.5797
52.93	11	at t = 0.55 T	0.6176	0.3354	0.0471	-	-	0.0577	0.6276	0.2912	0.0235	-	0.0235	0.0577	0.8059	0.0988	0.0141	0.0094	0.0288	0.1577	0.7794	0.0247	-	0.0047	0.0477	0.3359	0.6117
60.93	12	at t = 0.60 T	0.6656	0.2954	0.0391	-	-	0.0513	0.6620	0.2672	0.0195	-	0.0195	0.0513	0.8219	0.0956	0.0117	0.0078	0.0256	0.1513	0.7914	0.0239	-	0.0039	0.0413	0.3111	0.6437
68.50	13	at t = 0.65 T	0.7110	0.2575	0.0315	-	-	0.0452	0.6946	0.2445	0.0158	-	0.0158	0.0452	0.8370	0.0926	0.0095	0.0063	0.0226	0.1452	0.8028	0.0232	-	0.0032	0.0352	0.2877	0.6740
76.00	14	at t = 0.70 T	0.7560	0.2200	0.0240	-	-	0.0392	0.7268	0.2220	0.0120	-	0.0120	0.0392	0.8520	0.0896	0.0072	0.0048	0.0196	0.1392	0.8140	0.0224	-	0.0024	0.0292	0.2644	0.7040
83.00	15	at t = 0.75 T	0.7980	0.1850	0.0170	-	-	0.0336	0.7569	0.2010	0.0085	-	0.0085	0.0336	0.8660	0.0868	0.0051	0.0034	0.0168	0.1336	0.8245	0.0217	-	0.0017	0.0236	0.2427	0.7320
89.50	16	at t = 0.80 T	0.8370	0.1525	0.0105	-	-	0.0284	0.7849	0.1815	0.0053	-	0.0053	0.0284	0.8790	0.0842	0.0032	0.0021	0.0142	0.1284	0.8343	0.0211	-	0.0011	0.0184	0.2226	0.7580
93.50	17	at t = 0.85 T	0.8610	0.1325	0.0065	-	-	0.0252	0.8021	0.1695	0.0033	-	0.0033	0.0252	0.8870	0.0826	0.0020	0.0013	0.0126	0.1252	0.8403	0.0207	-	0.0007	0.0152	0.2102	0.7740
96.00	18	at t = 0.90 T	0.8760	0.1200	0.0040	-	-	0.0232	0.8128	0.1620	0.0020	-	0.0020	0.0232	0.8920	0.0816	0.0012	0.0008	0.0116	0.1232	0.8440	0.0204	-	0.0004	0.0132	0.2024	0.7840
98.50	19	at t = 0.95 T	0.8910	0.1075	0.0015	-	-	0.0212	0.8236	0.1545	0.0007	-	0.0007	0.0212	0.8970	0.0806	0.0004	0.0003	0.0106	0.1212	0.8478	0.0202	-	0.0002	0.0112	0.1947	0.7940
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0200	0.8300	0.1500	-	-	-	0.0200	0.9000	0.0800	-	-	0.0100	0.1200	0.8500	0.0200	-	-	0.0100	0.1900	0.8000


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Schedule Forecasting Model

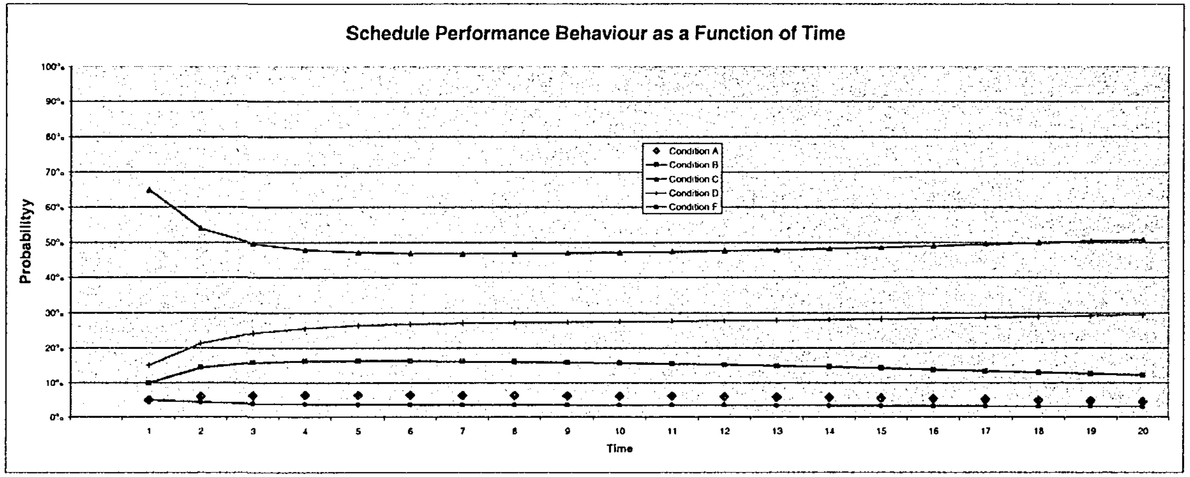
	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.3000**	**0.6000**	**0.1000**	-	-	0.3300	0.5750	0.0950	-	-	0.3510	0.5575	0.0915	-	-	0.3750	0.5375	0.0875	-	-
B						**0.1000**	**0.4000**	**0.4500**	**0.0500**	-	0.0960	0.4215	0.4350	0.0475	-	0.0932	0.4366	0.4245	0.0458	-	0.0900	0.4538	0.4125	0.0438	-
C						**0.0500**	**0.1000**	**0.7000**	**0.1200**	**0.0300**	0.0475	0.0960	0.7100	0.1180	0.0285	0.0458	0.0932	0.7170	0.1166	0.0275	0.0438	0.0900	0.7250	0.1150	0.0263
D						**0.0200**	**0.0500**	**0.2000**	**0.7000**	**0.0300**	0.0190	0.0480	0.1960	0.7075	0.0295	0.0183	0.0466	0.1932	0.7128	0.0292	0.0175	0.0450	0.1900	0.7188	0.0288
F						-	**0.0100**	**0.0900**	**0.5000**	**0.4000**	-	0.0095	0.0860	0.4845	0.4200	-	0.0092	0.0832	0.4737	0.4340	-	0.0088	0.0800	0.4613	0.4500

	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.4020	0.5150	0.0830	-	-	0.4346	0.4879	0.0776	-	-	0.4766	0.4529	0.0706	-	-	0.5216	0.4154	0.0631	-	-	0.5696	0.3754	0.0551	-	-
B	0.0864	0.4731	0.3990	0.0415	-	0.0821	0.4964	0.3827	0.0388	-	0.0765	0.5265	0.3617	0.0353	-	0.0705	0.5588	0.3392	0.0315	-	0.0641	0.5932	0.3152	0.0275	-
C	0.0415	0.0864	0.7340	0.1132	0.0249	0.0388	0.0821	0.7449	0.1110	0.0233	0.0353	0.0765	0.7589	0.1082	0.0212	0.0315	0.0705	0.7739	0.1052	0.0189	0.0275	0.0641	0.7899	0.1020	0.0165
D	0.0166	0.0432	0.1864	0.7255	0.0283	0.0155	0.0410	0.1821	0.7336	0.0278	0.0141	0.0382	0.1765	0.7441	0.0271	0.0126	0.0352	0.1705	0.7554	0.0263	0.0110	0.0320	0.1641	0.7674	0.0255
F	-	0.0083	0.0764	0.4473	0.4680	-	0.0078	0.0721	0.4305	0.4897	-	0.0071	0.0665	0.4088	0.5177	-	0.0063	0.0605	0.3855	0.5477	-	0.0055	0.0541	0.3607	0.5797

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6176	0.3354	0.0471	-	-	0.6656	0.2954	0.0391	-	-	0.7110	0.2575	0.0315	-	-	0.7560	0.2200	0.0240	-	-	0.7980	0.1850	0.0170	-	-
B	0.0577	0.6276	0.2912	0.0235	-	0.0513	0.6620	0.2672	0.0195	-	0.0452	0.6946	0.2445	0.0158	-	0.0392	0.7268	0.2220	0.0120	-	0.0336	0.7569	0.2010	0.0085	-
C	0.0235	0.0577	0.8059	0.0988	0.0141	0.0195	0.0513	0.8219	0.0956	0.0117	0.0158	0.0452	0.8370	0.0926	0.0095	0.0120	0.0392	0.8520	0.0896	0.0072	0.0085	0.0336	0.8660	0.0868	0.0051
D	0.0094	0.0288	0.1577	0.7794	0.0247	0.0078	0.0256	0.1513	0.7914	0.0239	0.0063	0.0226	0.1452	0.8028	0.0232	0.0048	0.0196	0.1392	0.8140	0.0224	0.0034	0.0168	0.1336	0.8245	0.0217
F	-	0.0047	0.0477	0.3359	0.6117	-	0.0039	0.0413	0.3111	0.6437	-	0.0032	0.0352	0.2877	0.6740	-	0.0024	0.0292	0.2644	0.7040	-	0.0017	0.0236	0.2427	0.7320

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8370	0.1525	0.0105	-	-	0.8610	0.1325	0.0065	-	-	0.8760	0.1200	0.0040	-	-	0.8910	0.1075	0.0015	-	-	**0.9000**	**0.1000**	-	-	-
B	0.0284	0.7849	0.1815	0.0053	-	0.0252	0.8021	0.1695	0.0033	-	0.0232	0.8128	0.1620	0.0020	-	0.0212	0.8236	0.1545	0.0007	-	**0.0200**	**0.8300**	**0.1500**	-	-
C	0.0053	0.0284	0.8790	0.0842	0.0032	0.0033	0.0252	0.8870	0.0826	0.0020	0.0020	0.0232	0.8920	0.0816	0.0012	0.0007	0.0212	0.8970	0.0806	0.0004	-	**0.0200**	**0.9000**	**0.0800**	-
D	0.0021	0.0142	0.1284	0.8343	0.0211	0.0013	0.0126	0.1252	0.8403	0.0207	0.0008	0.0116	0.1232	0.8440	0.0204	0.0003	0.0106	0.1212	0.8478	0.0202	-	**0.0100**	**0.1200**	**0.8500**	**0.0200**
F	-	0.0011	0.0184	0.2226	0.7580	-	0.0007	0.0152	0.2102	0.7740	-	0.0004	0.0132	0.2024	0.7840	-	0.0002	0.0112	0.1947	0.7940	-	-	**0.0100**	**0.1900**	**0.8000**

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Schedule Index	Expected Value	The expected schedule performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00 T			
	CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probab	State Proba	State Proba	State Prob	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	SPI	SPI	
	A		5%	6.05%	6.34%	6.41%	6.41%	6.38%	6.34%	6.29%	6.23%	6.16%	6.07%	5.97%	5.85%	5.72%	5.56%	5.37%	5.16%	4.95%	4.73%	4.51%	1.20	0.05	
	B		10%	14.30%	15.75%	16.20%	16.30%	16.25%	16.16%	16.02%	15.84%	15.64%	15.41%	15.14%	14.84%	14.51%	14.14%	13.73%	13.32%	12.93%	12.55%	12.19%	1.10	0.13	
Initial Probability Vector obtained from company historic records	C		65%	53.95%	49.65%	47.89%	47.15%	46.85%	46.77%	46.81%	46.92%	47.09%	47.31%	47.57%	47.87%	48.22%	48.61%	49.06%	49.50%	49.92%	50.34%	50.73%	1.00	0.51	
	D		15%	21.30%	24.25%	25.69%	26.44%	26.86%	27.11%	27.29%	27.43%	27.56%	27.70%	27.84%	27.99%	28.16%	28.35%	28.56%	28.79%	29.02%	29.25%	29.48%	0.90	0.27	98.56%
	F		5%	4.40%	4.01%	3.81%	3.71%	3.66%	3.63%	3.60%	3.58%	3.55%	3.52%	3.48%	3.44%	3.39%	3.34%	3.28%	3.23%	3.18%	3.13%	3.09%	0.80	0.02	or Within TARGET
	sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	0.986	
			1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99			


Schedule Performance Behaviour as a Function of Time

APPENDIX (J)

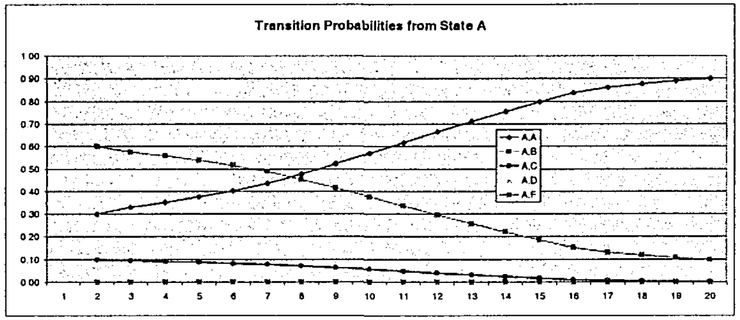
Forecasting Project Performance using Dynamic Markov Chains

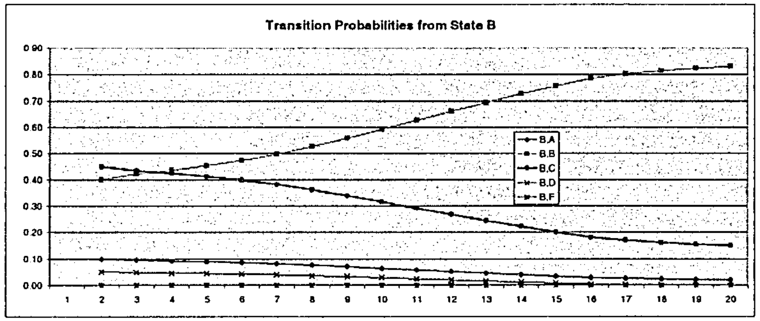
Schedule Forecasting Update

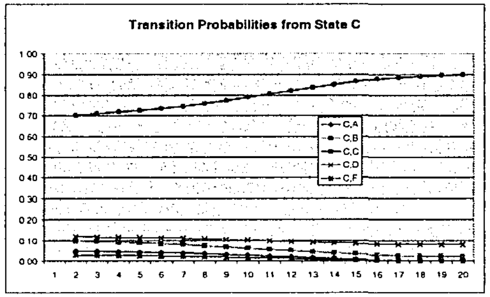
Transition Probabilities as a Function of Project Duration (T)

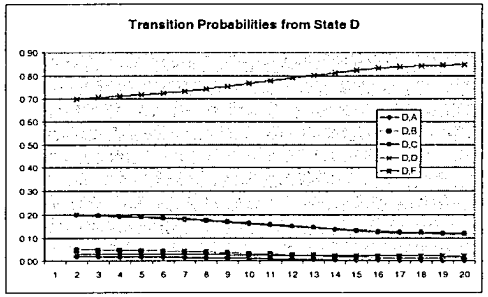
boundary conditions derived based on company historic database

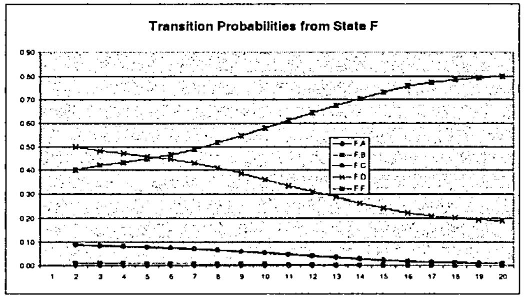
S-Curve By Manh	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	**0.3000**	**0.6000**	**0.1000**	-	-	**0.1000**	**0.4000**	**0.4500**	**0.0500**	-	**0.0500**	**0.1000**	**0.7000**	**0.1200**	**0.0300**	**0.0200**	**0.0500**	**0.2000**	**0.7000**	**0.0300**	-	**0.0100**	**0.0900**	**0.5000**	**0.4000**
5.00	3	at t = 0.15 T	0.3300	0.5750	0.0950	-	-	0.0960	0.4215	0.4350	0.0475	-	0.0475	0.0960	0.7100	0.1180	0.0285	0.0190	0.0480	0.1960	0.7075	0.0295	-	0.0095	0.0860	0.4845	0.4200
8.50	4	at t = 0.20 T	0.3510	0.5575	0.0915	-	-	0.0932	0.4366	0.4245	0.0458	-	0.0458	0.0932	0.7170	0.1166	0.0275	0.0183	0.0466	0.1932	0.7128	0.0292	-	0.0092	0.0832	0.4737	0.4340
12.50	5	at t = 0.25 T	0.3750	0.5375	0.0875	-	-	0.0900	0.4538	0.4125	0.0438	-	0.0438	0.0900	0.7250	0.1150	0.0263	0.0175	0.0450	0.1900	0.7188	0.0288	-	0.0088	0.0800	0.4613	0.4500
17.00	6	at t = 0.30 T	0.4020	0.5150	0.0830	-	-	0.0864	0.4731	0.3990	0.0415	-	0.0415	0.0864	0.7340	0.1132	0.0249	0.0166	0.0432	0.1864	0.7255	0.0283	-	0.0083	0.0764	0.4473	0.4680
22.43	7	at t = 0.35 T	0.4346	0.4879	0.0776	-	-	0.0821	0.4964	0.3827	0.0388	-	0.0388	0.0821	0.7449	0.1110	0.0233	0.0155	0.0410	0.1821	0.7336	0.0278	-	0.0078	0.0721	0.4305	0.4897
29.43	8	at t = 0.40 T	0.4766	0.4529	0.0706	-	-	0.0765	0.5265	0.3617	0.0353	-	0.0353	0.0765	0.7589	0.1082	0.0212	0.0141	0.0382	0.1765	0.7441	0.0271	-	0.0071	0.0665	0.4088	0.5177
36.93	9	at t = 0.45 T	0.5216	0.4154	0.0631	-	-	0.0705	0.5588	0.3392	0.0315	-	0.0315	0.0705	0.7739	0.1052	0.0189	0.0126	0.0352	0.1705	0.7554	0.0263	-	0.0063	0.0605	0.3855	0.5477
44.93	10	at t = 0.50 T	0.5696	0.3754	0.0551	-	-	0.0641	0.5932	0.3152	0.0275	-	0.0275	0.0641	0.7899	0.1020	0.0165	0.0110	0.0320	0.1641	0.7674	0.0255	-	0.0055	0.0541	0.3607	0.5797
52.93	11	at t = 0.55 T	0.6176	0.3354	0.0471	-	-	0.0577	0.6276	0.2912	0.0235	-	0.0235	0.0577	0.8059	0.0988	0.0141	0.0094	0.0288	0.1577	0.7794	0.0247	-	0.0047	0.0477	0.3359	0.6117
60.93	12	at t = 0.60 T	0.6656	0.2954	0.0391	-	-	0.0513	0.6620	0.2672	0.0195	-	0.0195	0.0513	0.8219	0.0956	0.0117	0.0078	0.0256	0.1513	0.7914	0.0239	-	0.0039	0.0413	0.3111	0.6437
68.50	13	at t = 0.65 T	0.7110	0.2575	0.0315	-	-	0.0452	0.6946	0.2445	0.0158	-	0.0158	0.0452	0.8370	0.0926	0.0095	0.0063	0.0226	0.1452	0.8028	0.0232	-	0.0032	0.0352	0.2877	0.6740
76.00	14	at t = 0.70 T	0.7560	0.2200	0.0240	-	-	0.0392	0.7268	0.2220	0.0120	-	0.0120	0.0392	0.8520	0.0896	0.0072	0.0048	0.0196	0.1392	0.8140	0.0224	-	0.0024	0.0292	0.2644	0.7040
83.00	15	at t = 0.75 T	0.7980	0.1850	0.0170	-	-	0.0336	0.7569	0.2010	0.0085	-	0.0085	0.0336	0.8660	0.0868	0.0051	0.0034	0.0168	0.1336	0.8245	0.0217	-	0.0017	0.0236	0.2427	0.7320
89.50	16	at t = 0.80 T	0.8370	0.1525	0.0105	-	-	0.0284	0.7849	0.1815	0.0053	-	0.0053	0.0284	0.8790	0.0842	0.0032	0.0021	0.0142	0.1284	0.8343	0.0211	-	0.0011	0.0184	0.2226	0.7580
93.50	17	at t = 0.85 T	0.8610	0.1325	0.0065	-	-	0.0252	0.8021	0.1695	0.0033	-	0.0033	0.0252	0.8870	0.0826	0.0020	0.0013	0.0126	0.1252	0.8403	0.0207	-	0.0007	0.0152	0.2102	0.7740
96.00	18	at t = 0.90 T	0.8760	0.1200	0.0040	-	-	0.0232	0.8128	0.1620	0.0020	-	0.0020	0.0232	0.8920	0.0816	0.0012	0.0008	0.0116	0.1232	0.8440	0.0204	-	0.0004	0.0132	0.2024	0.7840
98.50	19	at t = 0.95 T	0.8910	0.1075	0.0015	-	-	0.0212	0.8236	0.1545	0.0007	-	0.0007	0.0212	0.8970	0.0806	0.0004	0.0003	0.0106	0.1212	0.8478	0.0202	-	0.0002	0.0112	0.1947	0.7940
100.00	20	at t = 1.00 T	**0.9000**	**0.1000**	-	-	-	**0.0200**	**0.8300**	**0.1500**	-	-	-	**0.0200**	**0.9000**	**0.0800**	-	-	**0.0100**	**0.1200**	**0.8500**	**0.0200**	-	-	**0.0100**	**0.1900**	**0.8000**


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Schedule Forecasting Update

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.3000**	**0.6000**	**0.1000**	-	-	0.3300	0.5750	0.0950	-	-	0.3510	0.5575	0.0915	-	-	0.3750	0.5375	0.0875	-	-
B						**0.1000**	**0.4000**	**0.4500**	**0.0500**	-	0.0960	0.4215	0.4350	0.0475	-	0.0932	0.4366	0.4245	0.0458	-	0.0900	0.4538	0.4125	0.0438	-
C						**0.0500**	**0.1000**	**0.7000**	**0.1200**	**0.0300**	0.0475	0.0960	0.7100	0.1180	0.0285	0.0458	0.0932	0.7170	0.1166	0.0275	0.0438	0.0900	0.7250	0.1150	0.0263
D						**0.0200**	**0.0500**	**0.2000**	**0.7000**	**0.0300**	0.0190	0.0480	0.1960	0.7075	0.0295	0.0183	0.0466	0.1932	0.7128	0.0292	0.0175	0.0450	0.1900	0.7188	0.0288
F						-	**0.0100**	**0.0900**	**0.5000**	**0.4000**	-	0.0095	0.0860	0.4845	0.4200	-	0.0092	0.0832	0.4737	0.4340	-	0.0088	0.0800	0.4613	0.4500

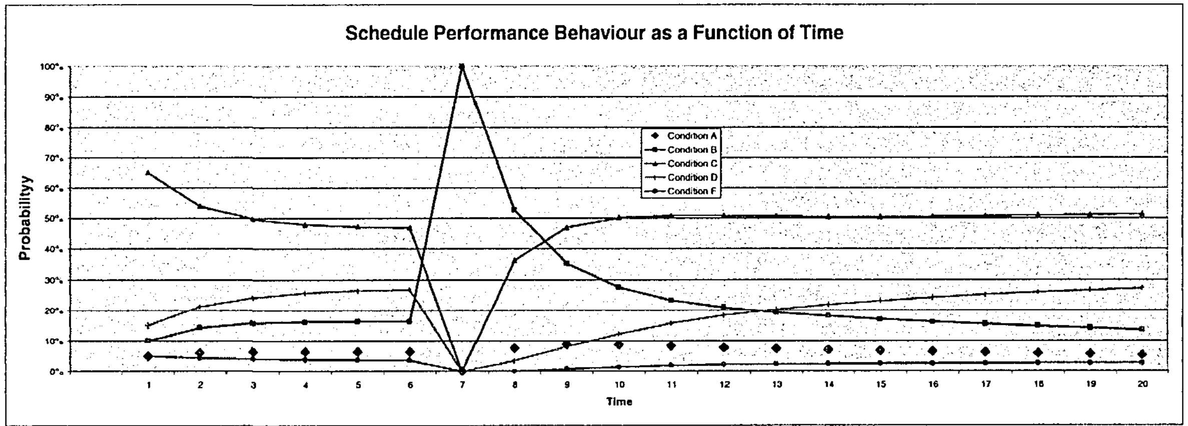
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.4020	0.5150	0.0830	-	-	0.4346	0.4879	0.0776	-	-	0.4766	0.4529	0.0706	-	-	0.5216	0.4154	0.0631	-	-	0.5696	0.3754	0.0551	-	-
B	0.0864	0.4731	0.3990	0.0415	-	0.0821	0.4964	0.3827	0.0388	-	0.0765	0.5265	0.3617	0.0353	-	0.0705	0.5588	0.3392	0.0315	-	0.0641	0.5932	0.3152	0.0275	-
C	0.0415	0.0864	0.7340	0.1132	0.0249	0.0388	0.0821	0.7449	0.1110	0.0233	0.0353	0.0765	0.7589	0.1082	0.0212	0.0315	0.0705	0.7739	0.1052	0.0189	0.0275	0.0641	0.7899	0.1020	0.0165
D	0.0166	0.0432	0.1864	0.7255	0.0283	0.0155	0.0410	0.1821	0.7336	0.0278	0.0141	0.0382	0.1765	0.7441	0.0271	0.0126	0.0352	0.1705	0.7554	0.0263	0.0110	0.0320	0.1641	0.7674	0.0255
F	-	0.0083	0.0764	0.4473	0.4680	-	0.0078	0.0721	0.4305	0.4897	-	0.0071	0.0665	0.4088	0.5177	-	0.0063	0.0605	0.3855	0.5477	-	0.0055	0.0541	0.3607	0.5797

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6176	0.3354	0.0471	-	-	0.6656	0.2954	0.0391	-	-	0.7110	0.2575	0.0315	-	-	0.7560	0.2200	0.0240	-	-	0.7980	0.1850	0.0170	-	-
B	0.0577	0.6276	0.2912	0.0235	-	0.0513	0.6620	0.2672	0.0195	-	0.0452	0.6946	0.2445	0.0158	-	0.0392	0.7268	0.2220	0.0120	-	0.0336	0.7569	0.2010	0.0085	-
C	0.0235	0.0577	0.8059	0.0988	0.0141	0.0195	0.0513	0.8219	0.0956	0.0117	0.0158	0.0452	0.8370	0.0926	0.0095	0.0120	0.0392	0.8520	0.0896	0.0072	0.0085	0.0336	0.8660	0.0868	0.0051
D	0.0094	0.0288	0.1577	0.7794	0.0247	0.0078	0.0256	0.1513	0.7914	0.0239	0.0063	0.0226	0.1452	0.8028	0.0232	0.0048	0.0196	0.1392	0.8140	0.0224	0.0034	0.0168	0.1336	0.8245	0.0217
F	-	0.0047	0.0477	0.3359	0.6117	-	0.0039	0.0413	0.3111	0.6437	-	0.0032	0.0352	0.2877	0.6740	-	0.0024	0.0292	0.2644	0.7040	-	0.0017	0.0236	0.2427	0.7320

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8370	0.1525	0.0105	-	-	0.8610	0.1325	0.0065	-	-	0.8760	0.1200	0.0040	-	-	0.8910	0.1075	0.0015	-	-	**0.9000**	**0.1000**	-	-	-
B	0.0284	0.7849	0.1815	0.0053	-	0.0252	0.8021	0.1695	0.0033	-	0.0232	0.8128	0.1620	0.0020	-	0.0212	0.8236	0.1545	0.0007	-	**0.0200**	**0.8300**	**0.1500**	-	-
C	0.0053	0.0284	0.8790	0.0842	0.0032	0.0033	0.0252	0.8870	0.0826	0.0020	0.0020	0.0232	0.8920	0.0816	0.0012	0.0007	0.0212	0.8970	0.0806	0.0004	-	**0.0200**	**0.9000**	**0.0800**	-
D	0.0021	0.0142	0.1284	0.8343	0.0211	0.0013	0.0126	0.1252	0.8403	0.0207	0.0008	0.0116	0.1232	0.8440	0.0204	0.0003	0.0106	0.1212	0.8478	0.0202	-	**0.0100**	**0.1200**	**0.8500**	**0.0200**
F	-	0.0011	0.0184	0.2226	0.7580	-	0.0007	0.0152	0.2102	0.7740	-	0.0004	0.0132	0.2024	0.7840	-	0.0002	0.0112	0.1947	0.7940	-	-	**0.0100**	**0.1900**	**0.8000**

Initial Probability Vector obtained from company historic records

Reporting Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Schedule Index	Expected Value	The expected schedule performance at the end of the project given the latest actual status is equal to :
	at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80 T	at t = 0.85 T	at t = 0.90 T	at t = 0.95 T	at t = 1.00 T			
CONDITION	State Proba	State Proba	State Proba	State Proba	State Probabi	State Probab	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	SPI	SPI	
A	5%	6.05%	6.34%	6.41%	6.41%	6.38%	0.00%	7.65%	8.88%	8.70%	8.25%	7.81%	7.41%	7.07%	6.75%	6.45%	6.15%	5.87%	5.59%	5.31%	1.20	0.06	
B	10%	14.30%	15.75%	16.20%	16.30%	16.25%	**100.00%**	52.65%	35.27%	27.53%	23.44%	20.97%	19.29%	18.04%	17.03%	16.16%	15.39%	14.72%	14.11%	13.56%	1.10	0.15	
C	65%	53.95%	49.65%	47.89%	47.15%	46.85%	0.00%	36.17%	46.94%	50.06%	50.77%	50.76%	50.59%	50.46%	50.43%	50.52%	50.67%	50.86%	51.07%	51.30%	1.00	0.51	
D	15%	21.30%	24.25%	25.69%	26.44%	26.86%	0.00%	3.53%	8.13%	12.28%	15.65%	18.28%	20.34%	21.95%	23.23%	24.29%	25.18%	25.94%	26.61%	27.20%	0.90	0.24	**99.17%**
F	5%	4.40%	4.01%	3.81%	3.71%	3.66%	0.00%	0.00%	0.78%	1.43%	1.89%	2.18%	2.37%	2.49%	2.56%	2.59%	2.60%	2.61%	2.62%	2.63%	0.80	0.02	or Within TARGET
sum	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	Total	0.9917	
	1.00	1.00	1.00	1.00	1.00	0.99	1.10	1.06	1.04	1.03	1.02	1.01	1.01	1.01	1.00	1.00	1.00	1.00	0.99	0.99			



APPENDIX (J)

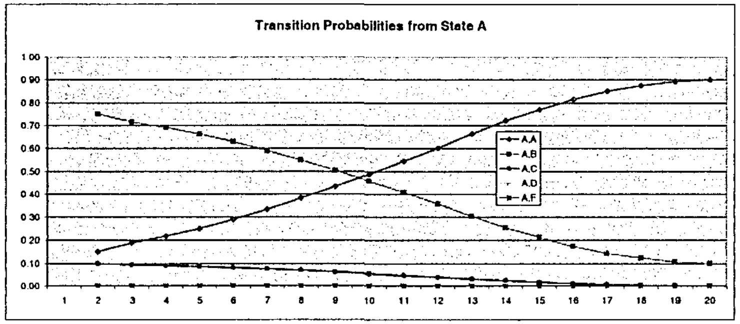
Forecasting Project Performance using Dynamic Markov Chains

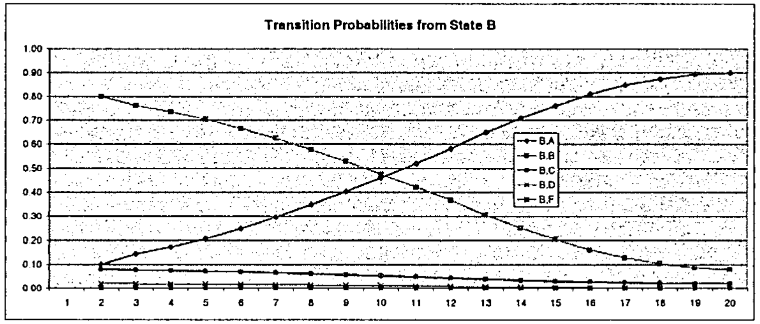
Billing Forecasting Model

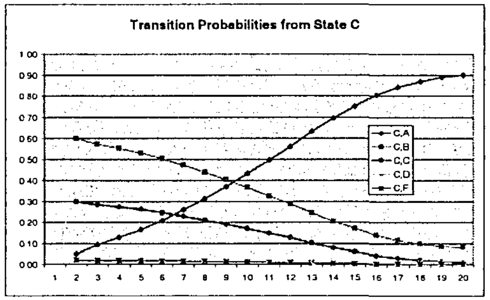
Transition Probabilities as a Function of Project Duration (T)

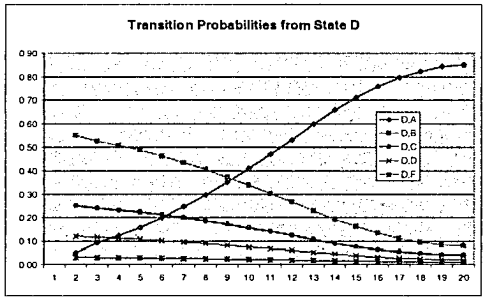
boundary conditions derived based on company historic database

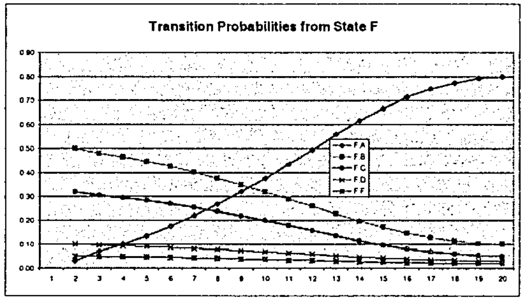
S-Curve Revenue	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.30	1	at t = 0.05 T																									
3.10	2	at t = 0.10 T	0.1500	0.7500	0.1000	-	-	0.1000	0.8000	0.0800	0.0200	-	0.0500	0.6000	0.3000	0.0300	0.0200	0.0500	0.5500	0.2500	0.1200	0.0300	0.0300	0.5000	0.3200	0.1000	0.0500
5.30	3	at t = 0.15 T	0.1898	0.7156	0.0947	-	-	0.1424	0.7618	0.0768	0.0189	-	0.0951	0.5724	0.2846	0.0289	0.0189	0.0924	0.5251	0.2389	0.1147	0.0289	0.0708	0.4788	0.3057	0.0963	0.0484
9.10	4	at t = 0.20 T	0.2183	0.6909	0.0909	-	-	0.1728	0.7345	0.0745	0.0182	-	0.1274	0.5527	0.2736	0.0282	0.0182	0.1228	0.5072	0.2309	0.1109	0.0282	0.1001	0.4636	0.2954	0.0936	0.0473
13.40	5	at t = 0.25 T	0.2505	0.6629	0.0866	-	-	0.2072	0.7035	0.0720	0.0173	-	0.1639	0.5303	0.2611	0.0273	0.0173	0.1572	0.4870	0.2219	0.1066	0.0273	0.1332	0.4464	0.2838	0.0906	0.0460
18.65	6	at t = 0.30 T	0.2899	0.6288	0.0814	-	-	0.2492	0.6657	0.0688	0.0163	-	0.2085	0.5030	0.2459	0.0263	0.0163	0.1992	0.4623	0.2108	0.1014	0.0263	0.1736	0.4254	0.2696	0.0869	0.0444
24.55	7	at t = 0.35 T	0.3341	0.5904	0.0755	-	-	0.2964	0.6232	0.0653	0.0151	-	0.2587	0.4723	0.2288	0.0251	0.0151	0.2464	0.4346	0.1984	0.0955	0.0251	0.2190	0.4018	0.2537	0.0828	0.0426
30.95	8	at t = 0.40 T	0.3821	0.5488	0.0691	-	-	0.3476	0.5772	0.0614	0.0138	-	0.3131	0.4391	0.2102	0.0238	0.0138	0.2976	0.4045	0.1850	0.0891	0.0238	0.2683	0.3762	0.2364	0.0783	0.0407
37.75	9	at t = 0.45 T	0.4331	0.5046	0.0623	-	-	0.4020	0.5282	0.0574	0.0125	-	0.3709	0.4037	0.1905	0.0225	0.0125	0.3520	0.3726	0.1707	0.0823	0.0225	0.3207	0.3490	0.2181	0.0736	0.0387
45.05	10	at t = 0.50 T	0.4879	0.4572	0.0550	-	-	0.4604	0.4756	0.0530	0.0110	-	0.4329	0.3657	0.1694	0.0210	0.0110	0.4104	0.3383	0.1554	0.0750	0.0210	0.3769	0.3198	0.1984	0.0685	0.0365
52.55	11	at t = 0.55 T	0.5441	0.4084	0.0475	-	-	0.5204	0.4216	0.0485	0.0095	-	0.4967	0.3267	0.1476	0.0195	0.0095	0.4704	0.3030	0.1396	0.0675	0.0195	0.4346	0.2898	0.1781	0.0632	0.0342
60.15	12	at t = 0.60 T	0.6011	0.3590	0.0399	-	-	0.5812	0.3669	0.0439	0.0080	-	0.5613	0.2872	0.1256	0.0180	0.0080	0.5312	0.2673	0.1237	0.0599	0.0180	0.4932	0.2594	0.1576	0.0579	0.0320
68.65	13	at t = 0.65 T	0.6649	0.3038	0.0314	-	-	0.6492	0.3057	0.0388	0.0063	-	0.6335	0.2430	0.1009	0.0163	0.0063	0.5992	0.2273	0.1058	0.0514	0.0163	0.5586	0.2254	0.1346	0.0519	0.0294
76.15	14	at t = 0.70 T	0.7211	0.2550	0.0239	-	-	0.7092	0.2517	0.0343	0.0048	-	0.6973	0.2040	0.0792	0.0148	0.0048	0.6592	0.1921	0.0901	0.0439	0.0148	0.6164	0.1954	0.1144	0.0467	0.0272
82.55	15	at t = 0.75 T	0.7691	0.2134	0.0175	-	-	0.7604	0.2056	0.0305	0.0035	-	0.7517	0.1707	0.0606	0.0135	0.0035	0.7104	0.1620	0.0766	0.0375	0.0135	0.6656	0.1698	0.0971	0.0422	0.0252
88.75	16	at t = 0.80 T	0.8156	0.1731	0.0113	-	-	0.8100	0.1610	0.0268	0.0023	-	0.8044	0.1385	0.0426	0.0123	0.0023	0.7600	0.1329	0.0636	0.0313	0.0123	0.7134	0.1450	0.0804	0.0379	0.0234
93.45	17	at t = 0.85 T	0.8509	0.1426	0.0066	-	-	0.8476	0.1272	0.0239	0.0013	-	0.8443	0.1141	0.0290	0.0113	0.0013	0.7976	0.1108	0.0538	0.0266	0.0113	0.7496	0.1262	0.0677	0.0346	0.0220
96.55	18	at t = 0.90 T	0.8741	0.1224	0.0034	-	-	0.8724	0.1048	0.0221	0.0007	-	0.8707	0.0979	0.0200	0.0107	0.0007	0.8224	0.0962	0.0472	0.0235	0.0107	0.7734	0.1138	0.0593	0.0324	0.0210
99.05	19	at t = 0.95 T	0.8929	0.1062	0.0009	-	-	0.8924	0.0868	0.0206	0.0002	-	0.8919	0.0849	0.0128	0.0102	0.0002	0.8424	0.0845	0.0420	0.0210	0.0102	0.7927	0.1038	0.0526	0.0307	0.0203
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.9000	0.0800	0.0200	-	-	0.9000	0.0800	0.0100	0.0100	-	0.8500	0.0800	0.0400	0.0200	0.0100	0.8000	0.1000	0.0500	0.0300	0.0200


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Billing Forecasting Model

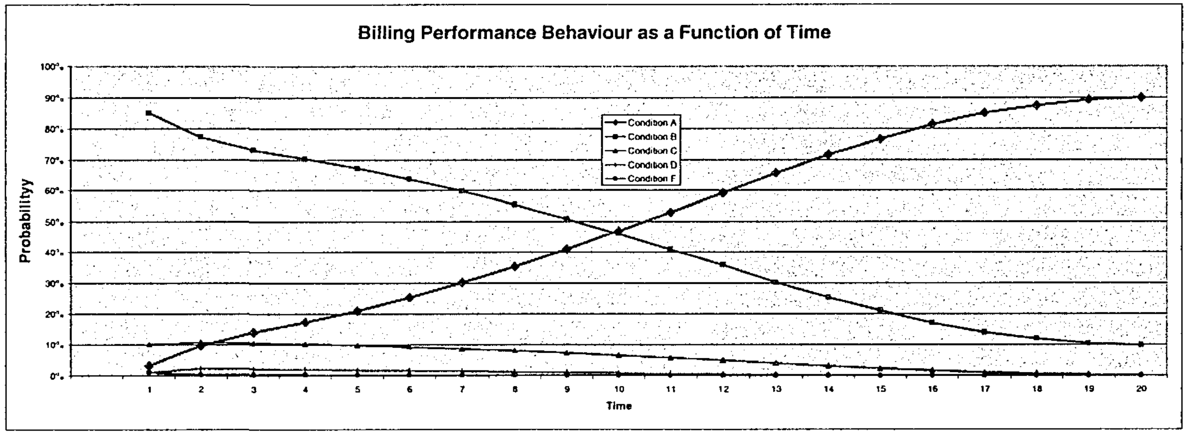
	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						0.1500	0.7500	0.1000	-	-	0.1898	0.7156	0.0947	-	-	0.2183	0.6909	0.0909	-	-	0.2505	0.6629	0.0866	-	-
B						0.1000	0.8000	0.0800	0.0200	-	0.1424	0.7618	0.0768	0.0189	-	0.1728	0.7345	0.0745	0.0182	-	0.2072	0.7035	0.0720	0.0173	-
C						0.0500	0.6000	0.3000	0.0300	0.0200	0.0951	0.5724	0.2846	0.0289	0.0189	0.1274	0.5527	0.2736	0.0282	0.0182	0.1639	0.5303	0.2611	0.0273	0.0173
D						0.0500	0.5500	0.2500	0.1200	0.0300	0.0924	0.5251	0.2389	0.1147	0.0289	0.1228	0.5072	0.2309	0.1109	0.0282	0.1572	0.4870	0.2219	0.1066	0.0273
F						0.0300	0.5000	0.3200	0.1000	0.0500	0.0708	0.4788	0.3057	0.0963	0.0484	0.1001	0.4636	0.2954	0.0936	0.0473	0.1332	0.4464	0.2838	0.0906	0.0460

	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.2899	0.6288	0.0814	-	-	0.3341	0.5904	0.0755	-	-	0.3821	0.5488	0.0691	-	-	0.4331	0.5046	0.0623	-	-	0.4879	0.4572	0.0550	-	-
B	0.2492	0.6657	0.0688	0.0163	-	0.2964	0.6232	0.0653	0.0151	-	0.3476	0.5772	0.0614	0.0138	-	0.4020	0.5282	0.0574	0.0125	-	0.4604	0.4756	0.0530	0.0110	-
C	0.2085	0.5030	0.2459	0.0263	0.0163	0.2587	0.4723	0.2288	0.0251	0.0151	0.3131	0.4391	0.2102	0.0238	0.0138	0.3709	0.4037	0.1905	0.0225	0.0125	0.4329	0.3657	0.1694	0.0210	0.0110
D	0.1992	0.4623	0.2108	0.1014	0.0263	0.2464	0.4346	0.1984	0.0955	0.0251	0.2976	0.4045	0.1850	0.0891	0.0238	0.3520	0.3726	0.1707	0.0823	0.0225	0.4104	0.3383	0.1554	0.0750	0.0210
F	0.1736	0.4254	0.2696	0.0869	0.0444	0.2190	0.4018	0.2537	0.0828	0.0426	0.2683	0.3762	0.2364	0.0783	0.0407	0.3207	0.3490	0.2181	0.0736	0.0387	0.3769	0.3198	0.1984	0.0685	0.0365

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5441	0.4084	0.0475	-	-	0.6011	0.3590	0.0399	-	-	0.6649	0.3038	0.0314	-	-	0.7211	0.2550	0.0239	-	-	0.7691	0.2134	0.0175	-	-
B	0.5204	0.4216	0.0485	0.0095	-	0.5812	0.3669	0.0439	0.0080	-	0.6492	0.3057	0.0388	0.0063	-	0.7092	0.2517	0.0343	0.0048	-	0.7604	0.2056	0.0305	0.0035	-
C	0.4967	0.3267	0.1476	0.0195	0.0095	0.5613	0.2872	0.1256	0.0180	0.0080	0.6335	0.2430	0.1009	0.0163	0.0063	0.6973	0.2040	0.0792	0.0148	0.0048	0.7517	0.1707	0.0606	0.0135	0.0035
D	0.4704	0.3030	0.1396	0.0675	0.0195	0.5312	0.2673	0.1237	0.0599	0.0180	0.5992	0.2273	0.1058	0.0514	0.0163	0.6592	0.1921	0.0901	0.0439	0.0148	0.7104	0.1620	0.0766	0.0375	0.0135
F	0.4346	0.2898	0.1781	0.0632	0.0342	0.4932	0.2594	0.1576	0.0579	0.0320	0.5586	0.2254	0.1346	0.0519	0.0294	0.6164	0.1954	0.1144	0.0467	0.0272	0.6656	0.1698	0.0971	0.0422	0.0252

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8156	0.1731	0.0113	-	-	0.8509	0.1426	0.0066	-	-	0.8741	0.1224	0.0034	-	-	0.8929	0.1062	0.0009	-	-	0.9000	0.1000	-	-	-
B	0.8100	0.1610	0.0268	0.0023	-	0.8476	0.1272	0.0239	0.0013	-	0.8724	0.1048	0.0221	0.0007	-	0.8924	0.0868	0.0206	0.0002	-	0.9000	0.0800	0.0200	-	-
C	0.8044	0.1385	0.0426	0.0123	0.0023	0.8443	0.1141	0.0290	0.0113	0.0013	0.8707	0.0979	0.0200	0.0107	0.0007	0.8919	0.0849	0.0128	0.0102	0.0002	0.9000	0.0800	0.0100	0.0100	-
D	0.7600	0.1329	0.0636	0.0313	0.0123	0.7976	0.1108	0.0538	0.0266	0.0113	0.8224	0.0962	0.0472	0.0235	0.0107	0.8424	0.0845	0.0420	0.0210	0.0102	0.8500	0.0800	0.0400	0.0200	0.0100
F	0.7134	0.1450	0.0804	0.0379	0.0234	0.7496	0.1262	0.0677	0.0346	0.0220	0.7734	0.1138	0.0593	0.0324	0.0210	0.7927	0.1038	0.0526	0.0307	0.0203	0.8000	0.1000	0.0500	0.0300	0.0200

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Billing Index	Expected Value	The expected billing performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80 T	at t = 0.85 T	at t = 0.90 T	at t = 0.95 T	at t = 1.00 T			
	CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probal	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	BPI	BPI	
	A		3%	9.53%	14.05%	17.32%	20.92%	25.27%	30.15%	35.42%	40.99%	46.91%	52.95%	59.03%	65.74%	71.64%	76.63%	81.41%	85.02%	87.38%	89.28%	90.00%	1.15	1.03	
	B		85%	77.30%	73.12%	70.38%	67.42%	63.81%	59.77%	55.41%	50.80%	45.87%	40.84%	35.76%	30.12%	25.19%	21.01%	16.98%	13.95%	11.97%	10.37%	9.79%	1.10	0.11	
Initial Probability Vector obtained from company historic records	C		10%	10.67%	10.49%	10.16%	9.71%	9.16%	8.53%	7.84%	7.11%	6.32%	5.51%	4.68%	3.77%	2.93%	2.21%	1.53%	0.99%	0.62%	0.34%	0.21%	1.00	0.00	
	D		1%	2.22%	2.05%	1.88%	1.72%	1.55%	1.36%	1.16%	0.97%	0.79%	0.62%	0.47%	0.33%	0.22%	0.14%	0.08%	0.04%	0.02%	0.01%	0.00%	0.90	0.00	114.48%
	F		1%	0.28%	0.28%	0.26%	0.24%	0.21%	0.19%	0.16%	0.13%	0.10%	0.08%	0.06%	0.04%	0.02%	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%	0.80	0.00	or ABOVE TARGET
	sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	1.145	
			1.09	1.09	1.09	1.09	1.10	1.10	1.10	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.14	1.14	1.14	1.14	1.14	1.14			



APPENDIX (J)

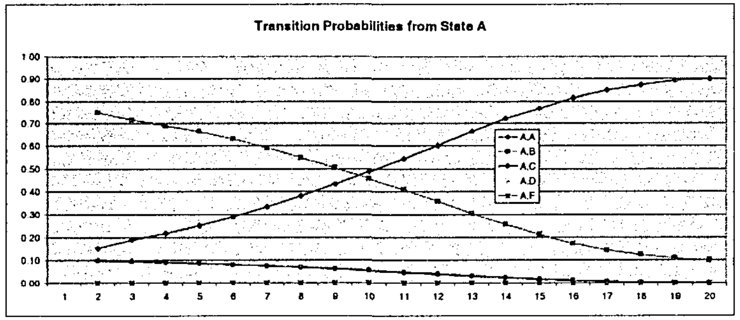
Forecasting Project Performance using Dynamic Markov Chains

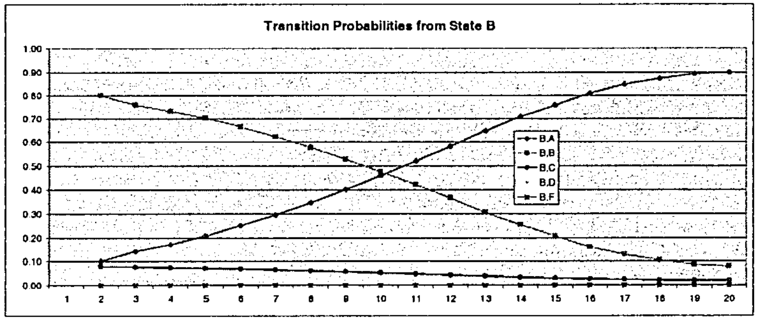
Billing Forecasting Update

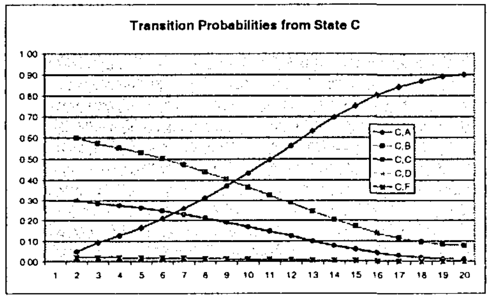
Transition Probabilities as a Function of Project Duration (T)

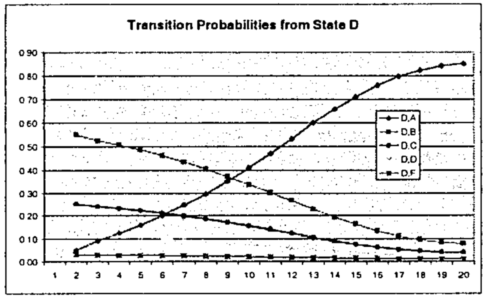
boundary conditions derived based on company historic database

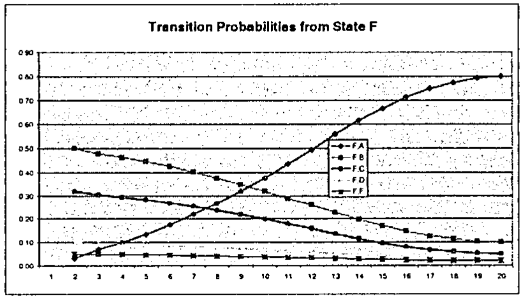
S-Curve Revenue	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.30	1	at t = 0.05 T																									
3.10	2	at t = 0.10 T	0.1500	0.7500	0.1000	-	-	0.1000	0.8000	0.0800	0.0200	-	0.0500	0.6000	0.3000	0.0300	0.0200	0.0500	0.5500	0.2500	0.1200	0.0300	0.0300	0.5000	0.3200	0.1000	0.0500
5.30	3	at t = 0.15 T	0.1898	0.7156	0.0947	-	-	0.1424	0.7618	0.0768	0.0189	-	0.0951	0.5724	0.2846	0.0289	0.0189	0.0924	0.5251	0.2389	0.1147	0.0289	0.0708	0.4788	0.3057	0.0963	0.0484
9.10	4	at t = 0.20 T	0.2183	0.6909	0.0909	-	-	0.1728	0.7345	0.0745	0.0182	-	0.1274	0.5527	0.2736	0.0282	0.0182	0.1228	0.5072	0.2309	0.1109	0.0282	0.1001	0.4636	0.2954	0.0936	0.0473
13.40	5	at t = 0.25 T	0.2505	0.6629	0.0866	-	-	0.2072	0.7035	0.0720	0.0173	-	0.1639	0.5303	0.2611	0.0273	0.0173	0.1572	0.4870	0.2219	0.1066	0.0273	0.1332	0.4464	0.2838	0.0906	0.0460
18.65	6	at t = 0.30 T	0.2899	0.6288	0.0814	-	-	0.2492	0.6657	0.0688	0.0163	-	0.2085	0.5030	0.2459	0.0263	0.0163	0.1992	0.4623	0.2108	0.1014	0.0263	0.1736	0.4254	0.2696	0.0869	0.0444
24.55	7	at t = 0.35 T	0.3341	0.5904	0.0755	-	-	0.2964	0.6232	0.0653	0.0151	-	0.2587	0.4723	0.2288	0.0251	0.0151	0.2464	0.4346	0.1984	0.0955	0.0251	0.2190	0.4018	0.2537	0.0828	0.0426
30.95	8	at t = 0.40 T	0.3821	0.5488	0.0691	-	-	0.3476	0.5772	0.0614	0.0138	-	0.3131	0.4391	0.2102	0.0238	0.0138	0.2976	0.4045	0.1850	0.0891	0.0238	0.2683	0.3762	0.2364	0.0783	0.0407
37.75	9	at t = 0.45 T	0.4331	0.5046	0.0623	-	-	0.4020	0.5282	0.0574	0.0125	-	0.3709	0.4037	0.1905	0.0225	0.0125	0.3520	0.3726	0.1707	0.0823	0.0225	0.3207	0.3490	0.2181	0.0736	0.0387
45.05	10	at t = 0.50 T	0.4879	0.4572	0.0550	-	-	0.4604	0.4756	0.0530	0.0110	-	0.4329	0.3657	0.1694	0.0210	0.0110	0.4104	0.3383	0.1554	0.0750	0.0210	0.3769	0.3198	0.1984	0.0685	0.0365
52.55	11	at t = 0.55 T	0.5441	0.4084	0.0475	-	-	0.5204	0.4216	0.0485	0.0095	-	0.4967	0.3267	0.1476	0.0195	0.0095	0.4704	0.3030	0.1396	0.0675	0.0195	0.4346	0.2898	0.1781	0.0632	0.0342
60.15	12	at t = 0.60 T	0.6011	0.3590	0.0399	-	-	0.5812	0.3669	0.0439	0.0080	-	0.5613	0.2872	0.1256	0.0180	0.0080	0.5312	0.2673	0.1237	0.0599	0.0180	0.4932	0.2594	0.1576	0.0579	0.0320
68.65	13	at t = 0.65 T	0.6649	0.3038	0.0314	-	-	0.6492	0.3057	0.0388	0.0063	-	0.6335	0.2430	0.1009	0.0163	0.0063	0.5992	0.2273	0.1058	0.0514	0.0163	0.5586	0.2254	0.1346	0.0519	0.0294
76.15	14	at t = 0.70 T	0.7211	0.2550	0.0239	-	-	0.7092	0.2517	0.0343	0.0048	-	0.6973	0.2040	0.0792	0.0148	0.0048	0.6592	0.1921	0.0901	0.0439	0.0148	0.6164	0.1954	0.1144	0.0467	0.0272
82.55	15	at t = 0.75 T	0.7691	0.2134	0.0175	-	-	0.7604	0.2056	0.0305	0.0035	-	0.7517	0.1707	0.0606	0.0135	0.0035	0.7104	0.1620	0.0766	0.0375	0.0135	0.6656	0.1698	0.0971	0.0422	0.0252
88.75	16	at t = 0.80 T	0.8156	0.1731	0.0113	-	-	0.8100	0.1610	0.0268	0.0023	-	0.8044	0.1385	0.0426	0.0123	0.0023	0.7600	0.1329	0.0636	0.0313	0.0123	0.7134	0.1450	0.0804	0.0379	0.0234
93.45	17	at t = 0.85 T	0.8509	0.1426	0.0066	-	-	0.8476	0.1272	0.0239	0.0013	-	0.8443	0.1141	0.0290	0.0113	0.0013	0.7976	0.1108	0.0538	0.0266	0.0113	0.7496	0.1262	0.0677	0.0346	0.0220
96.55	18	at t = 0.90 T	0.8741	0.1224	0.0034	-	-	0.8724	0.1048	0.0221	0.0007	-	0.8707	0.0979	0.0200	0.0107	0.0007	0.8224	0.0962	0.0472	0.0235	0.0107	0.7734	0.1138	0.0593	0.0324	0.0210
99.05	19	at t = 0.95 T	0.8929	0.1062	0.0009	-	-	0.8924	0.0868	0.0206	0.0002	-	0.8919	0.0849	0.0128	0.0102	0.0002	0.8424	0.0845	0.0420	0.0210	0.0102	0.7927	0.1038	0.0526	0.0307	0.0203
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.9000	0.0800	0.0200	-	-	0.9000	0.0800	0.0100	0.0100	-	0.8500	0.0800	0.0400	0.0200	0.0100	0.8000	0.1000	0.0500	0.0300	0.0200


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Billing Forecasting Update

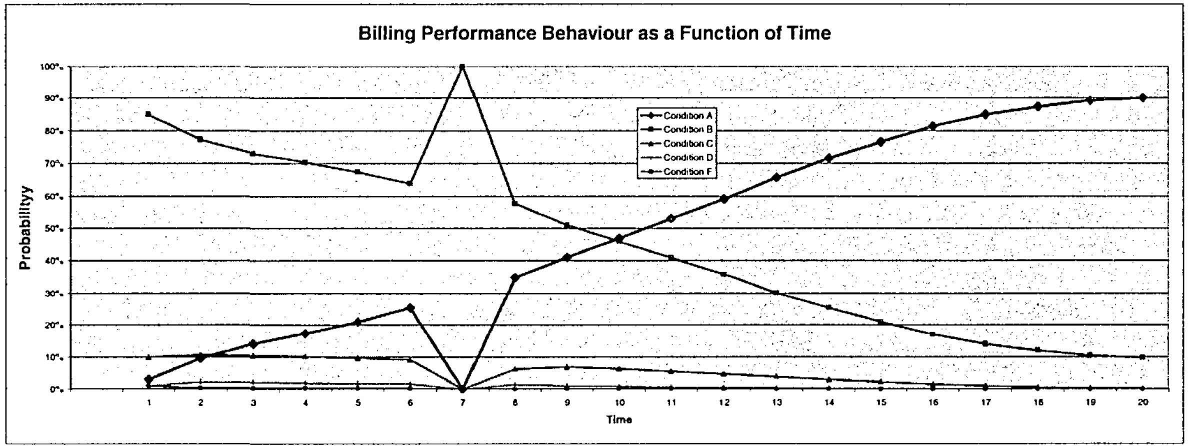
	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.1500**	**0.7500**	**0.1000**	-	-	0.1898	0.7156	0.0947	-	-	0.2183	0.6909	0.0909	-	-	0.2505	0.6629	0.0866	-	-
B						**0.1000**	**0.8000**	**0.0800**	**0.0200**	-	0.1424	0.7618	0.0768	0.0189	-	0.1728	0.7345	0.0745	0.0182	-	0.2072	0.7035	0.0720	0.0173	-
C						**0.0500**	**0.6000**	**0.3000**	**0.0300**	**0.0200**	0.0951	0.5724	0.2846	0.0289	0.0189	0.1274	0.5527	0.2736	0.0282	0.0182	0.1639	0.5303	0.2611	0.0273	0.0173
D						**0.0500**	**0.5500**	**0.2500**	**0.1200**	**0.0300**	0.0924	0.5251	0.2389	0.1147	0.0289	0.1228	0.5072	0.2309	0.1109	0.0282	0.1572	0.4870	0.2219	0.1066	0.0273
F						**0.0300**	**0.5000**	**0.3200**	**0.1000**	**0.0500**	0.0708	0.4788	0.3057	0.0963	0.0484	0.1001	0.4636	0.2954	0.0936	0.0473	0.1332	0.4464	0.2838	0.0906	0.0460

	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.2899	0.6288	0.0814	-	-	0.3341	0.5904	0.0755	-	-	0.3821	0.5488	0.0691	-	-	0.4331	0.5046	0.0623	-	-	0.4879	0.4572	0.0550	-	-
B	0.2492	0.6657	0.0688	0.0163	-	0.2964	0.6232	0.0653	0.0151	-	0.3476	0.5772	0.0614	0.0138	-	0.4020	0.5282	0.0574	0.0125	-	0.4604	0.4756	0.0530	0.0110	-
C	0.2085	0.5030	0.2459	0.0263	0.0163	0.2587	0.4723	0.2288	0.0251	0.0151	0.3131	0.4391	0.2102	0.0238	0.0138	0.3709	0.4037	0.1905	0.0225	0.0125	0.4329	0.3657	0.1694	0.0210	0.0110
D	0.1992	0.4623	0.2108	0.1014	0.0263	0.2464	0.4346	0.1984	0.0955	0.0251	0.2976	0.4045	0.1850	0.0891	0.0238	0.3520	0.3726	0.1707	0.0823	0.0225	0.4104	0.3383	0.1554	0.0750	0.0210
F	0.1736	0.4254	0.2696	0.0869	0.0444	0.2190	0.4018	0.2537	0.0828	0.0426	0.2683	0.3762	0.2364	0.0783	0.0407	0.3207	0.3490	0.2181	0.0736	0.0387	0.3769	0.3198	0.1984	0.0685	0.0365

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5441	0.4084	0.0475	-	-	0.6011	0.3590	0.0399	-	-	0.6649	0.3038	0.0314	-	-	0.7211	0.2550	0.0239	-	-	0.7691	0.2134	0.0175	-	-
B	0.5204	0.4216	0.0485	0.0095	-	0.5812	0.3669	0.0439	0.0080	-	0.6492	0.3057	0.0388	0.0063	-	0.7092	0.2517	0.0343	0.0048	-	0.7604	0.2056	0.0305	0.0035	-
C	0.4967	0.3267	0.1476	0.0195	0.0095	0.5613	0.2872	0.1256	0.0180	0.0080	0.6335	0.2430	0.1009	0.0163	0.0063	0.6973	0.2040	0.0792	0.0148	0.0048	0.7517	0.1707	0.0606	0.0135	0.0035
D	0.4704	0.3030	0.1396	0.0675	0.0195	0.5312	0.2673	0.1237	0.0599	0.0180	0.5992	0.2273	0.1058	0.0514	0.0163	0.6592	0.1921	0.0901	0.0439	0.0148	0.7104	0.1620	0.0766	0.0375	0.0135
F	0.4346	0.2898	0.1781	0.0632	0.0342	0.4932	0.2594	0.1576	0.0579	0.0320	0.5586	0.2254	0.1346	0.0519	0.0294	0.6164	0.1954	0.1144	0.0467	0.0272	0.6656	0.1698	0.0971	0.0422	0.0252

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8156	0.1731	0.0113	-	-	0.8509	0.1426	0.0066	-	-	0.8741	0.1224	0.0034	-	-	0.8929	0.1062	0.0009	-	-	**0.9000**	**0.1000**	-	-	-
B	0.8100	0.1610	0.0268	0.0023	-	0.8476	0.1272	0.0239	0.0013	-	0.8724	0.1048	0.0221	0.0007	-	0.8924	0.0868	0.0206	0.0002	-	**0.9000**	**0.0800**	**0.0200**	-	-
C	0.8044	0.1385	0.0426	0.0123	0.0023	0.8443	0.1141	0.0290	0.0113	0.0013	0.8707	0.0979	0.0200	0.0107	0.0007	0.8919	0.0849	0.0128	0.0102	0.0002	**0.9000**	**0.0800**	**0.0100**	**0.0100**	-
D	0.7600	0.1329	0.0636	0.0313	0.0123	0.7976	0.1108	0.0538	0.0266	0.0113	0.8224	0.0962	0.0472	0.0235	0.0107	0.8424	0.0845	0.0420	0.0210	0.0102	**0.8500**	**0.0800**	**0.0400**	**0.0200**	**0.0100**
F	0.7134	0.1450	0.0804	0.0379	0.0234	0.7496	0.1262	0.0677	0.0346	0.0220	0.7734	0.1138	0.0593	0.0324	0.0210	0.7927	0.1038	0.0526	0.0307	0.0203	**0.8000**	**0.1000**	**0.0500**	**0.0300**	**0.0200**

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Billing Index	Expected Value	The expected billing performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80 T	at t = 0.85 T	at t = 0.90 T	at t = 0.95 T	at t = 1.00 T			
	CONDITION		State Proba	State Proba	State Prob.	State Proba	State Probabi	State Probab	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prob	State Prob	State Prob	State Prob	State Proba	BPI	BPI	
	A		**3%**	9.53%	14.05%	17.32%	20.92%	25.27%	0.00%	34.76%	41.02%	**46.92%**	**52.96%**	**59.03%**	**65.74%**	**71.64%**	**76.63%**	81.41%	85.02%	87.38%	89.28%	90.00%	1.15	1.03	
	B		**85%**	77.30%	73.12%	70.38%	67.42%	63.81%	**100.00%**	57.72%	51.02%	**45.90%**	**40.84%**	**35.76%**	**30.12%**	**25.19%**	**21.01%**	16.98%	13.95%	11.97%	10.37%	9.79%	1.10	0.11	
Initial Probability Vector obtained from company historic records	C		**10%**	10.67%	10.49%	10.16%	9.71%	9.16%	0.00%	6.14%	6.88%	**6.29%**	**5.51%**	**4.68%**	**3.77%**	**2.93%**	**2.21%**	1.53%	0.99%	0.62%	0.34%	0.21%	1.00	0.00	
	D		**1%**	2.22%	2.05%	1.88%	1.72%	1.55%	0.00%	1.38%	0.97%	**0.79%**	**0.62%**	**0.47%**	**0.33%**	**0.22%**	**0.14%**	0.08%	0.04%	0.02%	0.01%	0.00%	0.90	0.00	114.48%
	F		**1%**	0.28%	0.28%	0.26%	0.24%	0.21%	0.00%	0.00%	0.11%	**0.10%**	**0.08%**	**0.06%**	**0.04%**	**0.02%**	**0.01%**	0.01%	0.00%	0.00%	0.00%	0.00%	0.80	0.00	or Within TARGET
	sum		**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	Total	1.145	
			1.09	1.09	1.09	1.09	1.10	1.10	1.10	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.14	1.14	1.14	1.14	1.14	1.14			



APPENDIX (J)

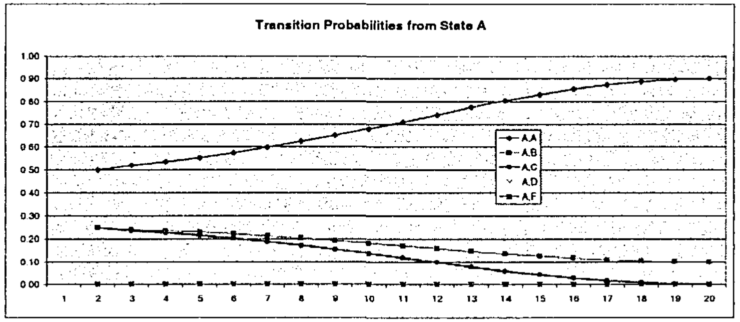
Forecasting Project Performance using Dynamic Markov Chains

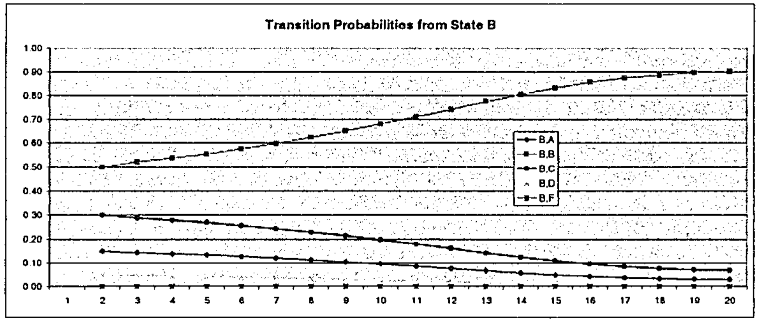
Profitability Forecasting Model

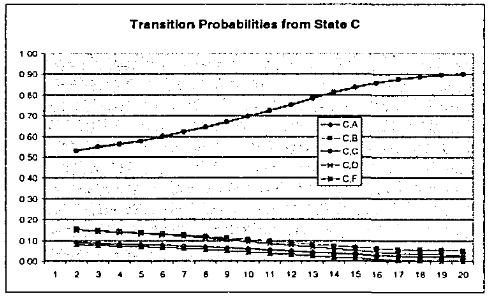
Transition Probabilities as a Function of Project Duration (T)

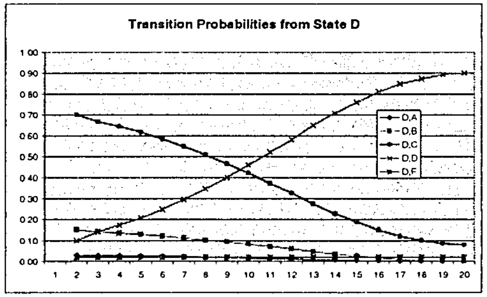
boundary conditions derived based on company historic database

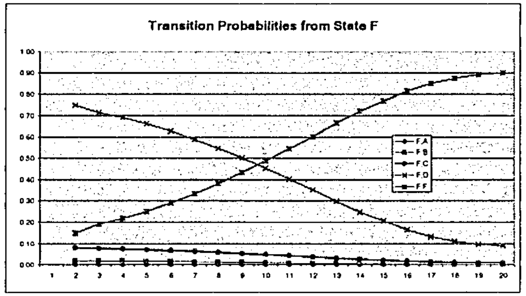
S-Curve Revenue	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.30	1	at t = 0.05 T																									
3.10	2	at t = 0.10 T	0.5000	0.2500	0.2500	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1500	0.5300	0.1500	0.0800	0.0300	0.1500	0.7000	0.1000	0.0200	-	0.0200	0.0800	0.7500	0.1500
5.30	3	at t = 0.15 T	0.5212	0.2421	0.2368	-	-	0.1436	0.5212	0.2878	0.0474	-	0.0863	0.1447	0.5496	0.1436	0.0758	0.0284	0.1421	0.6671	0.1424	0.0200	-	0.0189	0.0763	0.7150	0.1898
9.10	4	at t = 0.20 T	0.5364	0.2364	0.2273	-	-	0.1391	0.5364	0.2791	0.0455	-	0.0836	0.1409	0.5637	0.1391	0.0727	0.0273	0.1364	0.6436	0.1728	0.0200	-	0.0182	0.0736	0.6899	0.2183
13.40	5	at t = 0.25 T	0.5536	0.2299	0.2165	-	-	0.1339	0.5536	0.2692	0.0433	-	0.0806	0.1366	0.5796	0.1339	0.0693	0.0260	0.1299	0.6169	0.2072	0.0200	-	0.0173	0.0706	0.6616	0.2505
18.65	6	at t = 0.30 T	0.5746	0.2220	0.2034	-	-	0.1276	0.5746	0.2571	0.0407	-	0.0769	0.1314	0.5990	0.1276	0.0651	0.0244	0.1220	0.5844	0.2492	0.0200	-	0.0163	0.0669	0.6269	0.2899
24.55	7	at t = 0.35 T	0.5982	0.2132	0.1886	-	-	0.1205	0.5982	0.2435	0.0377	-	0.0728	0.1255	0.6208	0.1205	0.0604	0.0226	0.1132	0.5478	0.2964	0.0200	-	0.0151	0.0628	0.5880	0.3341
30.95	8	at t = 0.40 T	0.6238	0.2036	0.1726	-	-	0.1129	0.6238	0.2288	0.0345	-	0.0683	0.1191	0.6445	0.1129	0.0552	0.0207	0.1036	0.5081	0.3476	0.0200	-	0.0138	0.0583	0.5457	0.3821
37.75	9	at t = 0.45 T	0.6510	0.1934	0.1556	-	-	0.1047	0.6510	0.2132	0.0311	-	0.0636	0.1123	0.6697	0.1047	0.0498	0.0187	0.0934	0.4660	0.4020	0.0200	-	0.0125	0.0536	0.5009	0.4331
45.05	10	at t = 0.50 T	0.6802	0.1824	0.1374	-	-	0.0959	0.6802	0.1964	0.0275	-	0.0585	0.1050	0.6967	0.0959	0.0440	0.0165	0.0824	0.4207	0.4604	0.0200	-	0.0110	0.0485	0.4527	0.4879
52.55	11	at t = 0.55 T	0.7102	0.1712	0.1186	-	-	0.0869	0.7102	0.1791	0.0237	-	0.0532	0.0975	0.7244	0.0869	0.0380	0.0142	0.0712	0.3742	0.5204	0.0200	-	0.0095	0.0432	0.4032	0.5441
60.15	12	at t = 0.60 T	0.7406	0.1598	0.0996	-	-	0.0778	0.7406	0.1617	0.0199	-	0.0479	0.0899	0.7526	0.0778	0.0319	0.0120	0.0598	0.3271	0.5812	0.0200	-	0.0080	0.0379	0.3530	0.6011
68.65	13	at t = 0.65 T	0.7746	0.1470	0.0784	-	-	0.0676	0.7746	0.1421	0.0157	-	0.0419	0.0814	0.7840	0.0676	0.0251	0.0094	0.0470	0.2744	0.6492	0.0200	-	0.0063	0.0319	0.2969	0.6649
76.15	14	at t = 0.70 T	0.8046	0.1358	0.0596	-	-	0.0586	0.8046	0.1249	0.0119	-	0.0367	0.0739	0.8118	0.0586	0.0191	0.0072	0.0358	0.2279	0.7092	0.0200	-	0.0048	0.0267	0.2474	0.7211
82.55	15	at t = 0.75 T	0.8302	0.1262	0.0436	-	-	0.0509	0.8302	0.1101	0.0087	-	0.0322	0.0675	0.8354	0.0509	0.0140	0.0052	0.0262	0.1882	0.7604	0.0200	-	0.0035	0.0222	0.2052	0.7691
88.75	16	at t = 0.80 T	0.8550	0.1169	0.0281	-	-	0.0435	0.8550	0.0959	0.0056	-	0.0279	0.0613	0.8584	0.0435	0.0090	0.0034	0.0169	0.1498	0.8100	0.0200	-	0.0023	0.0179	0.1643	0.8156
93.45	17	at t = 0.85 T	0.8738	0.1098	0.0164	-	-	0.0379	0.8738	0.0851	0.0033	-	0.0246	0.0566	0.8758	0.0379	0.0052	0.0020	0.0098	0.1206	0.8476	0.0200	-	0.0013	0.0146	0.1332	0.8509
96.55	18	at t = 0.90 T	0.8862	0.1052	0.0086	-	-	0.0341	0.8862	0.0779	0.0017	-	0.0224	0.0535	0.8872	0.0341	0.0028	0.0010	0.0052	0.1014	0.8724	0.0200	-	0.0007	0.0124	0.1128	0.8741
99.05	19	at t = 0.95 T	0.8962	0.1014	0.0024	-	-	0.0311	0.8962	0.0722	0.0005	-	0.0207	0.0510	0.8965	0.0311	0.0008	0.0003	0.0014	0.0859	0.8924	0.0200	-	0.0002	0.0107	0.0963	0.8929
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0800	0.9000	0.0200	-	-	0.0100	0.0900	0.9000


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Profitability Forecasting Model

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.5000**	**0.2500**	**0.2500**	**-**	**-**	0.5212	0.2421	0.2368	-	-	0.5364	0.2364	0.2273	-	-	0.5536	0.2299	0.2165	-	-
B						**0.1500**	**0.5000**	**0.3000**	**0.0500**	**-**	0.1436	0.5212	0.2878	0.0474	-	0.1391	0.5364	0.2791	0.0455	-	0.1339	0.5536	0.2692	0.0433	-
C						**0.0900**	**0.1500**	**0.5300**	**0.1500**	**0.0800**	0.0863	0.1447	0.5496	0.1436	0.0758	0.0836	0.1409	0.5637	0.1391	0.0727	0.0806	0.1366	0.5796	0.1339	0.0693
D						**0.0300**	**0.1500**	**0.7000**	**0.1000**	**0.0200**	0.0284	0.1421	0.6671	0.1424	0.0200	0.0273	0.1364	0.6436	0.1728	0.0200	0.0260	0.1299	0.6169	0.2072	0.0200
F						**-**	**0.0200**	**0.0800**	**0.7500**	**0.1500**	-	0.0189	0.0763	0.7150	0.1898	-	0.0182	0.0736	0.6899	0.2183	-	0.0173	0.0706	0.6616	0.2505

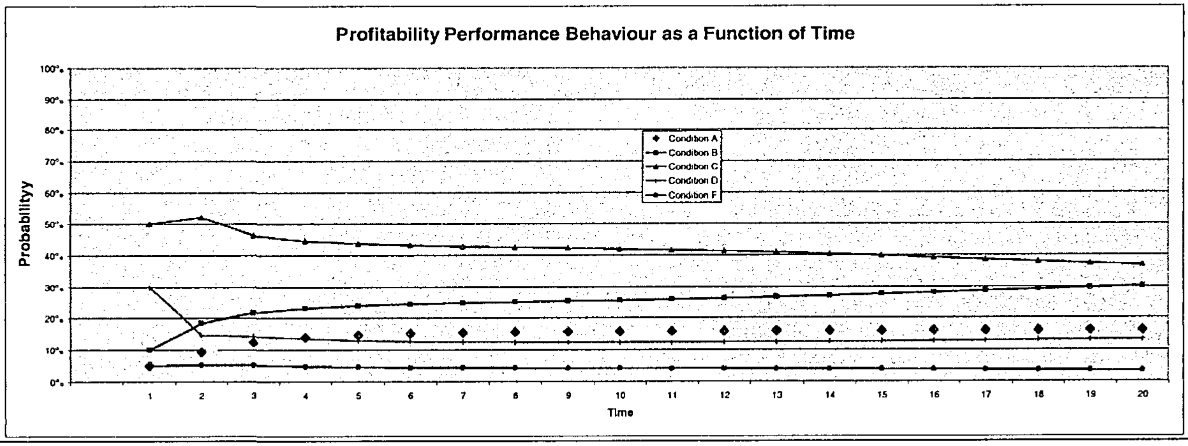
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5746	0.2220	0.2034	-	-	0.5982	0.2132	0.1886	-	-	0.6238	0.2036	0.1726	-	-	0.6510	0.1934	0.1556	-	-	0.6802	0.1824	0.1374	-	-
B	0.1276	0.5746	0.2571	0.0407	-	0.1205	0.5982	0.2435	0.0377	-	0.1129	0.6238	0.2288	0.0345	-	0.1047	0.6510	0.2132	0.0311	-	0.0959	0.6802	0.1964	0.0275	-
C	0.0769	0.1314	0.5990	0.1276	0.0651	0.0728	0.1255	0.6208	0.1205	0.0604	0.0683	0.1191	0.6445	0.1129	0.0552	0.0636	0.1123	0.6697	0.1047	0.0498	0.0585	0.1050	0.6967	0.0959	0.0440
D	0.0244	0.1220	0.5844	0.2492	0.0200	0.0226	0.1132	0.5478	0.2964	0.0200	0.0207	0.1036	0.5081	0.3476	0.0200	0.0187	0.0934	0.4660	0.4020	0.0200	0.0165	0.0824	0.4207	0.4604	0.0200
F	-	0.0163	0.0669	0.6269	0.2899	-	0.0151	0.0628	0.5880	0.3341	-	0.0138	0.0583	0.5457	0.3821	-	0.0125	0.0536	0.5009	0.4331	-	0.0110	0.0485	0.4527	0.4879

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7102	0.1712	0.1186	-	-	0.7406	0.1598	0.0996	-	-	0.7746	0.1470	0.0784	-	-	0.8046	0.1358	0.0596	-	-	0.8302	0.1262	0.0436	-	-
B	0.0869	0.7102	0.1791	0.0237	-	0.0778	0.7406	0.1617	0.0199	-	0.0676	0.7746	0.1421	0.0157	-	0.0586	0.8046	0.1249	0.0119	-	0.0509	0.8302	0.1101	0.0087	-
C	0.0532	0.0975	0.7244	0.0869	0.0380	0.0479	0.0899	0.7526	0.0778	0.0319	0.0419	0.0814	0.7840	0.0676	0.0251	0.0367	0.0739	0.8118	0.0586	0.0191	0.0322	0.0675	0.8354	0.0509	0.0140
D	0.0142	0.0712	0.3742	0.5204	0.0200	0.0120	0.0598	0.3271	0.5812	0.0200	0.0094	0.0470	0.2744	0.6492	0.0200	0.0072	0.0358	0.2279	0.7092	0.0200	0.0052	0.0262	0.1882	0.7604	0.0200
F	-	0.0095	0.0432	0.4032	0.5441	-	0.0080	0.0379	0.3530	0.6011	-	0.0063	0.0319	0.2969	0.6649	-	0.0048	0.0267	0.2474	0.7211	-	0.0035	0.0222	0.2052	0.7691

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8550	0.1169	0.0281	-	-	0.8738	0.1098	0.0164	-	-	0.8862	0.1052	0.0086	-	-	0.8962	0.1014	0.0024	-	-	**0.9000**	**0.1000**	**-**	**-**	**-**
B	0.0435	0.8550	0.0959	0.0056	-	0.0379	0.8738	0.0851	0.0033	-	0.0341	0.8862	0.0779	0.0017	-	0.0311	0.8962	0.0722	0.0005	-	**0.0300**	**0.9000**	**0.0700**	**-**	**-**
C	0.0279	0.0613	0.8584	0.0435	0.0090	0.0246	0.0566	0.8758	0.0379	0.0052	0.0224	0.0535	0.8872	0.0341	0.0028	0.0207	0.0510	0.8965	0.0311	0.0008	**0.0200**	**0.0500**	**0.9000**	**0.0300**	**-**
D	0.0034	0.0169	0.1498	0.8100	0.0200	0.0020	0.0098	0.1206	0.8476	0.0200	0.0010	0.0052	0.1014	0.8724	0.0200	0.0003	0.0014	0.0859	0.8924	0.0200	**-**	**-**	**0.0800**	**0.9000**	**0.0200**
F	-	0.0023	0.0179	0.1643	0.8156	-	0.0013	0.0146	0.1332	0.8509	-	0.0007	0.0124	0.1128	0.8741	-	0.0002	0.0107	0.0963	0.8929	**-**	**-**	**0.0100**	**0.0900**	**0.9000**

Initial Probability Vector obtained from company historic records

Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Profitability Index	Expected Value	The expected profitability performance at the end of the project given the latest actual status is equal to :
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80 T	at t = 0.85 T	at t = 0.90 T	at t = 0.95 T	at t = 1.00 T			
CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probab	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prob	State Prob	State Prob	State Prob	State Proba	PPI	PPI	
A		5%	9.40%	12.45%	13.95%	14.77%	15.22%	15.49%	15.65%	15.75%	15.82%	15.88%	15.92%	15.96%	16.00%	16.03%	16.06%	16.09%	16.12%	16.15%	16.18%	1.20	0.19	
B		10%	18.35%	21.58%	23.10%	23.93%	24.44%	24.79%	25.08%	25.34%	25.62%	25.92%	26.25%	26.65%	27.10%	27.59%	28.13%	28.70%	29.26%	29.82%	30.32%	1.10	0.33	
C		50%	52.15%	46.42%	44.60%	43.78%	43.26%	42.89%	42.59%	42.31%	42.03%	41.72%	41.37%	40.95%	40.46%	39.93%	39.33%	38.70%	38.06%	37.43%	36.86%	1.00	0.37	
D		30%	14.75%	14.29%	13.53%	12.96%	12.65%	12.49%	12.41%	12.37%	12.36%	12.38%	12.41%	12.47%	12.54%	12.63%	12.75%	12.89%	13.02%	13.16%	13.28%	0.90	0.12	104.27 %
F		5%	5.35%	5.26%	4.81%	4.57%	4.43%	4.34%	4.28%	4.22%	4.17%	4.11%	4.05%	3.98%	3.90%	3.81%	3.72%	3.63%	3.54%	3.45%	3.37%	0.80	0.03	or Within TARGET
sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	1.043	
		0.98	1.01	1.02	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04			



APPENDIX (J)

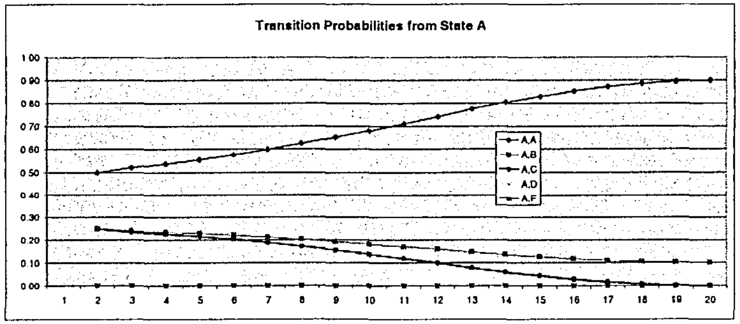
Forecasting Project Performance using Dynamic Markov Chains

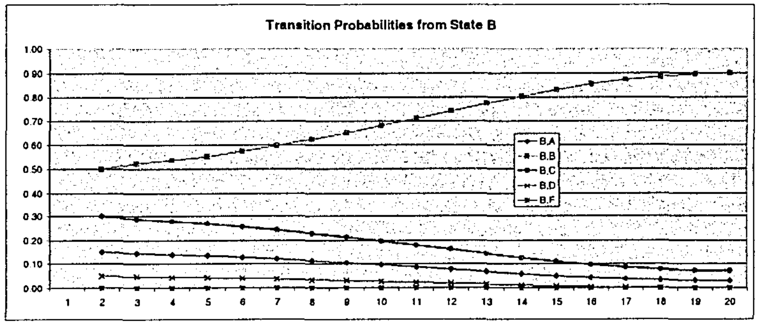
Profitability Forecasting Update

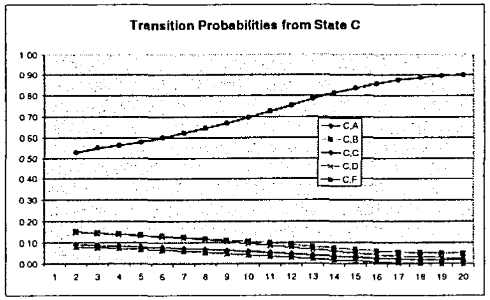
Transition Probabilities as a Function of Project Duration (T)

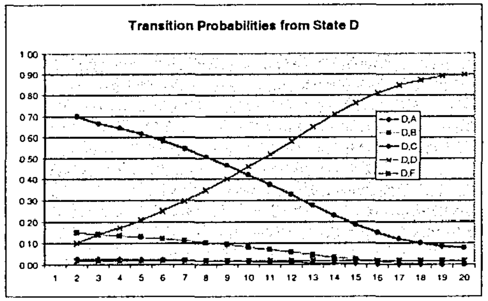
boundary conditions derived based on company historic database

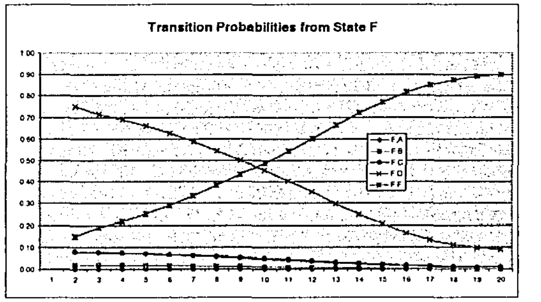
S-Curve Revenue	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.30	1	at t = 0.05 T																									
3.10	2	at t = 0.10 T	0.5000	0.2500	0.2500	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1500	0.5300	0.1500	0.0800	0.0300	0.1500	0.7000	0.1000	0.0200	-	0.0200	0.0800	0.7500	0.1500
5.30	3	at t = 0.15 T	0.5212	0.2421	0.2368	-	-	0.1436	0.5212	0.2878	0.0474	-	0.0863	0.1447	0.5496	0.1436	0.0758	0.0284	0.1421	0.6671	0.1424	0.0200	-	0.0189	0.0763	0.7150	0.1898
9.10	4	at t = 0.20 T	0.5364	0.2364	0.2273	-	-	0.1391	0.5364	0.2791	0.0455	-	0.0836	0.1409	0.5637	0.1391	0.0727	0.0273	0.1364	0.6436	0.1728	0.0200	-	0.0182	0.0736	0.6899	0.2183
13.40	5	at t = 0.25 T	0.5536	0.2299	0.2165	-	-	0.1339	0.5536	0.2692	0.0433	-	0.0806	0.1366	0.5796	0.1339	0.0693	0.0260	0.1299	0.6169	0.2072	0.0200	-	0.0173	0.0706	0.6616	0.2505
18.65	6	at t = 0.30 T	0.5746	0.2220	0.2034	-	-	0.1276	0.5746	0.2571	0.0407	-	0.0769	0.1314	0.5990	0.1276	0.0651	0.0244	0.1220	0.5844	0.2492	0.0200	-	0.0163	0.0669	0.6269	0.2899
24.55	7	at t = 0.35 T	0.5982	0.2132	0.1886	-	-	0.1205	0.5982	0.2435	0.0377	-	0.0728	0.1255	0.6208	0.1205	0.0604	0.0226	0.1132	0.5478	0.2964	0.0200	-	0.0151	0.0628	0.5880	0.3341
30.95	8	at t = 0.40 T	0.6238	0.2036	0.1726	-	-	0.1129	0.6238	0.2288	0.0345	-	0.0683	0.1191	0.6445	0.1129	0.0552	0.0207	0.1036	0.5081	0.3476	0.0200	-	0.0138	0.0583	0.5457	0.3821
37.75	9	at t = 0.45 T	0.6510	0.1934	0.1556	-	-	0.1047	0.6510	0.2132	0.0311	-	0.0636	0.1123	0.6697	0.1047	0.0498	0.0187	0.0934	0.4660	0.4020	0.0200	-	0.0125	0.0536	0.5009	0.4331
45.05	10	at t = 0.50 T	0.6802	0.1824	0.1374	-	-	0.0959	0.6802	0.1964	0.0275	-	0.0585	0.1050	0.6967	0.0959	0.0440	0.0165	0.0824	0.4207	0.4604	0.0200	-	0.0110	0.0485	0.4527	0.4879
52.55	11	at t = 0.55 T	0.7102	0.1712	0.1186	-	-	0.0869	0.7102	0.1791	0.0237	-	0.0532	0.0975	0.7244	0.0869	0.0380	0.0142	0.0712	0.3742	0.5204	0.0200	-	0.0095	0.0432	0.4032	0.5441
60.15	12	at t = 0.60 T	0.7406	0.1598	0.0996	-	-	0.0778	0.7406	0.1617	0.0199	-	0.0479	0.0899	0.7526	0.0778	0.0319	0.0120	0.0598	0.3271	0.5812	0.0200	-	0.0080	0.0379	0.3530	0.6011
68.65	13	at t = 0.65 T	0.7746	0.1470	0.0784	-	-	0.0676	0.7746	0.1421	0.0157	-	0.0419	0.0814	0.7840	0.0676	0.0251	0.0094	0.0470	0.2744	0.6492	0.0200	-	0.0063	0.0319	0.2969	0.6649
76.15	14	at t = 0.70 T	0.8046	0.1358	0.0596	-	-	0.0586	0.8046	0.1249	0.0119	-	0.0367	0.0739	0.8118	0.0586	0.0191	0.0072	0.0358	0.2279	0.7092	0.0200	-	0.0048	0.0267	0.2474	0.7211
82.55	15	at t = 0.75 T	0.8302	0.1262	0.0436	-	-	0.0509	0.8302	0.1101	0.0087	-	0.0322	0.0675	0.8354	0.0509	0.0140	0.0052	0.0262	0.1882	0.7604	0.0200	-	0.0035	0.0222	0.2052	0.7691
88.75	16	at t = 0.80 T	0.8550	0.1169	0.0281	-	-	0.0435	0.8550	0.0959	0.0056	-	0.0279	0.0613	0.8584	0.0435	0.0090	0.0034	0.0169	0.1498	0.8100	0.0200	-	0.0023	0.0179	0.1643	0.8156
93.45	17	at t = 0.85 T	0.8738	0.1098	0.0164	-	-	0.0379	0.8738	0.0851	0.0033	-	0.0246	0.0566	0.8758	0.0379	0.0052	0.0020	0.0098	0.1206	0.8476	0.0200	-	0.0013	0.0146	0.1332	0.8509
96.55	18	at t = 0.90 T	0.8862	0.1052	0.0086	-	-	0.0341	0.8862	0.0779	0.0017	-	0.0224	0.0535	0.8872	0.0341	0.0028	0.0010	0.0052	0.1014	0.8724	0.0200	-	0.0007	0.0124	0.1128	0.8741
99.05	19	at t = 0.95 T	0.8962	0.1014	0.0024	-	-	0.0311	0.8962	0.0722	0.0005	-	0.0207	0.0510	0.8965	0.0311	0.0008	0.0003	0.0014	0.0859	0.8924	0.0200	-	0.0002	0.0107	0.0963	0.8929
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0800	0.9000	0.0200	-	-	0.0100	0.0900	0.9000


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Profitability Forecasting Update

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.5000**	**0.2500**	**0.2500**	**-**	**-**	0.5212	0.2421	0.2368	-	-	0.5364	0.2364	0.2273	-	-	0.5536	0.2299	0.2165	-	-
B						**0.1500**	**0.5000**	**0.3000**	**0.0500**	**-**	0.1436	0.5212	0.2878	0.0474	-	0.1391	0.5364	0.2791	0.0455	-	0.1339	0.5536	0.2692	0.0433	-
C						**0.0900**	**0.1500**	**0.5300**	**0.1500**	**0.0800**	0.0863	0.1447	0.5496	0.1436	0.0758	0.0836	0.1409	0.5637	0.1391	0.0727	0.0806	0.1366	0.5796	0.1339	0.0693
D						**0.0300**	**0.1500**	**0.7000**	**0.1000**	**0.0200**	0.0284	0.1421	0.6671	0.1424	0.0200	0.0273	0.1364	0.6436	0.1728	0.0200	0.0260	0.1299	0.6169	0.2072	0.0200
F						**-**	**0.0200**	**0.0800**	**0.7500**	**0.1500**	-	0.0189	0.0763	0.7150	0.1898	-	0.0182	0.0736	0.6899	0.2183	-	0.0173	0.0706	0.6616	0.2505

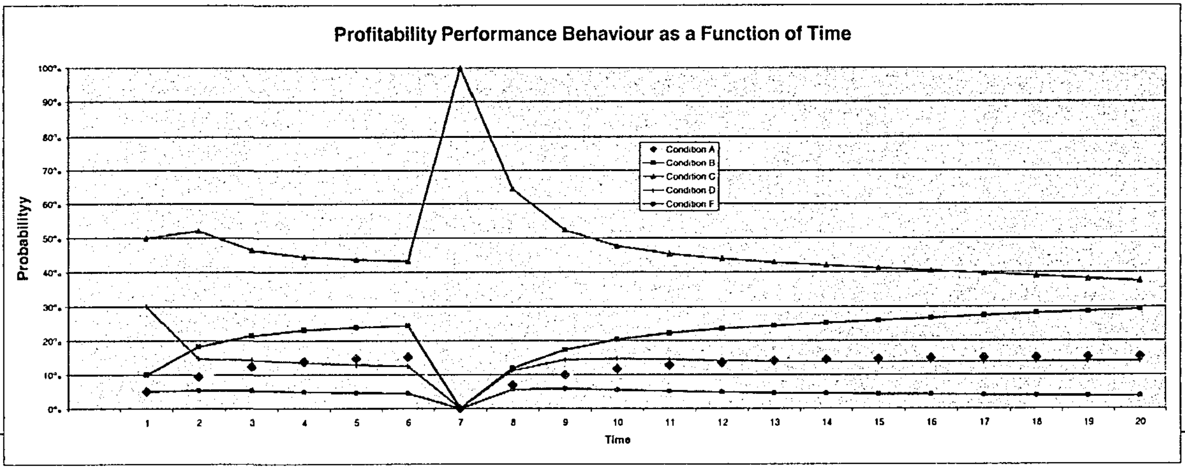
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5746	0.2220	0.2034	-	-	0.5982	0.2132	0.1886	-	-	0.6238	0.2036	0.1726	-	-	0.6510	0.1934	0.1556	-	-	0.6802	0.1824	0.1374	-	-
B	0.1276	0.5746	0 2571	0.0407	-	0.1205	0 5982	0.2435	0.0377	-	0.1129	0.6238	0.2288	0.0345	-	0.1047	0.6510	0.2132	0.0311	-	0.0959	0.6802	0.1964	0.0275	-
C	0.0769	0.1314	0.5990	0.1276	0.0651	0.0728	0.1255	0.6208	0.1205	0.0604	0.0683	0.1191	0.6445	0.1129	0.0552	0.0636	0.1123	0.6697	0.1047	0.0498	0.0585	0.1050	0.6967	0.0959	0.0440
D	0.0244	0.1220	0.5844	0.2492	0.0200	0.0226	0.1132	0.5478	0.2964	0.0200	0.0207	0.1036	0.5081	0.3476	0.0200	0.0187	0.0934	0.4660	0.4020	0.0200	0.0165	0.0824	0.4207	0.4604	0.0200
F	-	0.0163	0.0669	0.6269	0.2899	-	0.0151	0.0628	0.5880	0.3341	-	0.0138	0.0583	0.5457	0.3821	-	0.0125	0.0536	0.5009	0.4331	-	0.0110	0.0485	0.4527	0.4879

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7102	0.1712	0.1186	-	-	0.7406	0.1598	0.0996	-	-	0.7746	0.1470	0.0784	-	-	0.8046	0.1358	0.0596	-	-	0.8302	0.1262	0.0436	-	-
B	0.0869	0.7102	0.1791	0.0237	-	0.0778	0.7406	0.1617	0.0199	-	0.0676	0.7746	0.1421	0.0157	-	0.0586	0.8046	0.1249	0.0119	-	0.0509	0.8302	0.1101	0.0087	-
C	0.0532	0.0975	0.7244	0 0869	0.0380	0.0479	0.0899	0.7526	0.0778	0.0319	0.0419	0.0814	0.7840	0.0676	0.0251	0.0367	0.0739	0.8118	0.0586	0.0191	0.0322	0.0675	0.8354	0.0509	0.0140
D	0.0142	0.0712	0.3742	0.5204	0.0200	0.0120	0.0598	0.3271	0.5812	0.0200	0.0094	0.0470	0.2744	0.6492	0.0200	0.0072	0.0358	0.2279	0.7092	0.0200	0.0052	0.0262	0.1882	0.7604	0.0200
F	-	0.0095	0.0432	0.4032	0.5441	-	0.0080	0.0379	0.3530	0.6011	-	0.0063	0.0319	0.2969	0.6649	-	0.0048	0.0267	0.2474	0.7211	-	0.0035	0.0222	0.2052	0.7691

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8550	0.1169	0.0281	-	-	0.8738	0.1098	0.0164	-	-	0.8862	0.1052	0.0086	-	-	0.8962	0.1014	0.0024	-	-	**0.9000**	**0.1000**	**-**	**-**	**-**
B	0.0435	0.8550	0.0959	0.0056	-	0.0379	0.8738	0.0851	0.0033	-	0.0341	0.8862	0.0779	0.0017	-	0.0311	0.8962	0.0722	0.0005	-	**0.0300**	**0.9000**	**0.0700**	**-**	**-**
C	0.0279	0.0613	0.8584	0.0435	0.0090	0.0246	0.0566	0.8758	0.0379	0.0052	0.0224	0.0535	0.8872	0.0341	0.0028	0.0207	0.0510	0.8965	0.0311	0.0008	**0.0200**	**0.0500**	**0.9000**	**0.0300**	**-**
D	0.0034	0.0169	0.1498	0.8100	0.0200	0.0020	0.0098	0.1206	0.8476	0.0200	0.0010	0.0052	0.1014	0.8724	0.0200	0.0003	0.0014	0.0859	0.8924	0.0200	-	-	**0.0800**	**0.9000**	**0.0200**
F	-	0.0023	0.0179	0.1643	0.8156	-	0.0013	0.0146	0.1332	0.8509	-	0.0007	0.0124	0.1128	0.8741	-	0.0002	0.0107	0.0963	0.8929	-	-	**0.0100**	**0.0900**	**0.9000**

Initial Probability Vector obtained from company historic records

Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Profitability Index	Expected Value	The expected profitability performance at the end of the project given the latest actual status is equal to :
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00 T			
CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probab	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	PPI	PPI	
A		5%	9.40%	12.45%	13.95%	14.77%	15.22%	0.00%	6.83%	10.00%	11.77%	12.88%	13.61%	14.11%	14.46%	14.72%	14.92%	15.07%	15.19%	15.30%	15.39%	1.20	0.18	
B		10%	18.35%	21.58%	23.10%	23.93%	24.44%	0.00%	11.91%	17.43%	20.42%	22.26%	23.52%	24.49%	25.31%	26.05%	26.76%	27.45%	28.10%	28.73%	29.29%	1.10	0.32	
C		50%	52.15%	46.42%	44.60%	43.78%	43.26%	100.00%	64.45%	52.32%	47.60%	45.30%	43.91%	42.88%	42.01%	41.21%	40.43%	39.65%	38.90%	38.18%	37.53%	1.00	0.38	
D		30%	14.75%	14.29%	13.53%	12.96%	12.65%	0.00%	11.29%	14.42%	14.78%	14.50%	14.18%	13.96%	13.84%	13.78%	13.80%	13.86%	13.94%	14.04%	14.12%	0.90	0.13	103.86%
F		5%	5.35%	5.26%	4.81%	4.57%	4.43%	0.00%	5.52%	5.83%	5.43%	5.06%	4.77%	4.56%	4.39%	4.24%	4.10%	3.98%	3.86%	3.76%	3.66%	0.80	0.03	or Within TARGET
sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	1.039	
		0.98	1.01	1.02	1.03	1.03	1.03	1.00	1.00	1.01	1.02	1.02	1.03	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04			



APPENDIX (J)

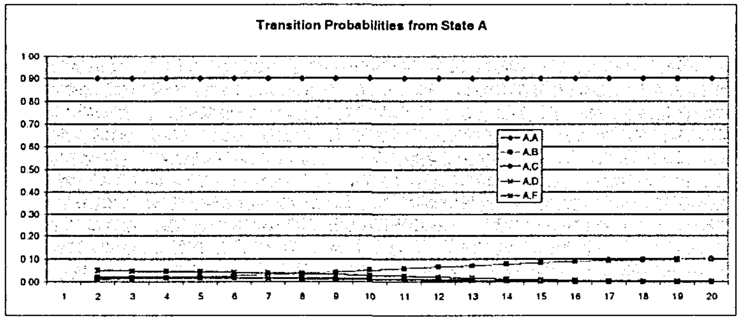
Forecasting Project Performance using Dynamic Markov Chains

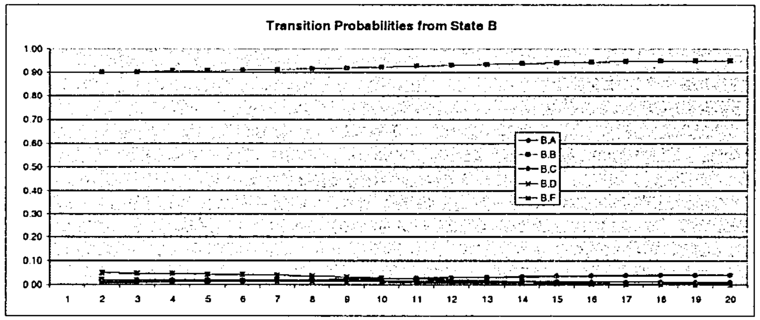
Safety Forecasting Model

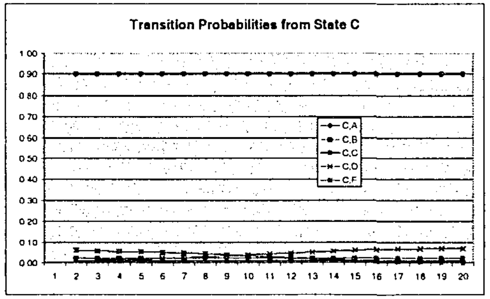
Transition Probabilities as a Function of Project Duration (T)

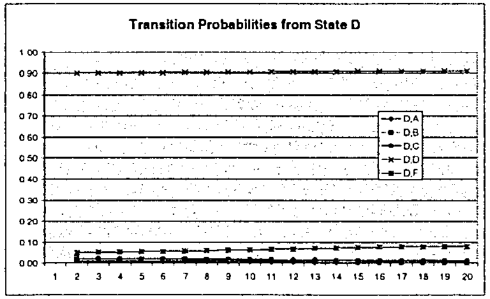
boundary conditions derived based on company historic database

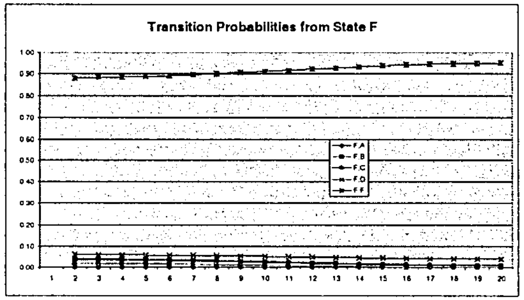
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	**0.9000**	**0.0100**	**0.0200**	**0.0200**	**0.0500**	**0.0200**	**0.9000**	**0.0100**	**0.0200**	**0.0500**	**0.0100**	**0.0200**	**0.9000**	**0.0100**	**0.0600**	**0.0100**	**0.0200**	**0.0200**	**0.9000**	**0.0500**	-	**0.0200**	**0.0400**	**0.0600**	**0.8800**
5.00	3	at t = 0.15 T	0.9000	0.0145	0.0190	0.0190	0.0475	0.0195	0.9025	0.0115	0.0190	0.0475	0.0100	0.0200	0.9000	0.0130	0.0570	0.0095	0.0190	0.0195	0.9005	0.0515	-	0.0190	0.0385	0.0590	0.8835
8.50	4	at t = 0.20 T	0.9000	0.0177	0.0183	0.0183	0.0458	0.0192	0.9043	0.0126	0.0183	0.0458	0.0100	0.0200	0.9000	0.0151	0.0549	0.0092	0.0183	0.0192	0.9009	0.0526	-	0.0183	0.0375	0.0583	0.8860
12.50	5	at t = 0.25 T	0.9000	0.0213	0.0175	0.0175	0.0438	0.0188	0.9063	0.0138	0.0175	0.0438	0.0100	0.0200	0.9000	0.0175	0.0525	0.0088	0.0175	0.0188	0.9013	0.0538	-	0.0175	0.0363	0.0575	0.8888
17.00	6	at t = 0.30 T	0.9000	0.0253	0.0166	0.0166	0.0415	0.0183	0.9085	0.0151	0.0166	0.0415	0.0100	0.0200	0.9000	0.0202	0.0498	0.0083	0.0166	0.0183	0.9017	0.0551	-	0.0166	0.0349	0.0566	0.8919
22.43	7	at t = 0.35 T	0.9000	0.0302	0.0155	0.0155	0.0388	0.0178	0.9112	0.0167	0.0155	0.0388	0.0100	0.0200	0.9000	0.0235	0.0465	0.0078	0.0155	0.0178	0.9022	0.0567	-	0.0155	0.0333	0.0555	0.8957
29.43	8	at t = 0.40 T	0.9000	0.0365	0.0141	0.0141	0.0353	0.0171	0.9147	0.0188	0.0141	0.0353	0.0100	0.0200	0.9000	0.0277	0.0423	0.0071	0.0141	0.0171	0.9029	0.0588	-	0.0141	0.0312	0.0541	0.9006
36.93	9	at t = 0.45 T	0.9000	0.0432	0.0126	0.0126	0.0315	0.0163	0.9185	0.0211	0.0126	0.0315	0.0100	0.0200	0.9000	0.0322	0.0378	0.0063	0.0126	0.0163	0.9037	0.0611	-	0.0126	0.0289	0.0526	0.9059
44.93	10	at t = 0.50 T	0.9000	0.0504	0.0110	0.0110	0.0275	0.0155	0.9225	0.0235	0.0110	0.0275	0.0100	0.0200	0.9000	0.0370	0.0330	0.0055	0.0110	0.0155	0.9045	0.0635	-	0.0110	0.0265	0.0510	0.9115
52.93	11	at t = 0.55 T	0.9000	0.0576	0.0094	0.0094	0.0235	0.0147	0.9265	0.0259	0.0094	0.0235	0.0100	0.0200	0.9000	0.0418	0.0282	0.0047	0.0094	0.0147	0.9053	0.0659	-	0.0094	0.0241	0.0494	0.9171
60.93	12	at t = 0.60 T	0.9000	0.0648	0.0078	0.0078	0.0195	0.0139	0.9305	0.0283	0.0078	0.0195	0.0100	0.0200	0.9000	0.0466	0.0234	0.0039	0.0078	0.0139	0.9061	0.0683	-	0.0078	0.0217	0.0478	0.9227
68.50	13	at t = 0.65 T	0.9000	0.0717	0.0063	0.0063	0.0158	0.0132	0.9343	0.0306	0.0063	0.0158	0.0100	0.0200	0.9000	0.0511	0.0189	0.0032	0.0063	0.0132	0.9069	0.0706	-	0.0063	0.0195	0.0463	0.9280
76.00	14	at t = 0.70 T	0.9000	0.0784	0.0048	0.0048	0.0120	0.0124	0.9380	0.0328	0.0048	0.0120	0.0100	0.0200	0.9000	0.0556	0.0144	0.0024	0.0048	0.0124	0.9076	0.0728	-	0.0048	0.0172	0.0448	0.9332
83.00	15	at t = 0.75 T	0.9000	0.0847	0.0034	0.0034	0.0085	0.0117	0.9415	0.0349	0.0034	0.0085	0.0100	0.0200	0.9000	0.0598	0.0102	0.0017	0.0034	0.0117	0.9083	0.0749	-	0.0034	0.0151	0.0434	0.9381
89.50	16	at t = 0.80 T	0.9000	0.0906	0.0021	0.0021	0.0053	0.0111	0.9448	0.0369	0.0021	0.0053	0.0100	0.0200	0.9000	0.0637	0.0063	0.0011	0.0021	0.0111	0.9090	0.0769	-	0.0021	0.0132	0.0421	0.9427
93.50	17	at t = 0.85 T	0.9000	0.0942	0.0013	0.0013	0.0033	0.0107	0.9468	0.0381	0.0013	0.0033	0.0100	0.0200	0.9000	0.0661	0.0039	0.0007	0.0013	0.0107	0.9094	0.0781	-	0.0013	0.0120	0.0413	0.9455
96.00	18	at t = 0.90 T	0.9000	0.0964	0.0008	0.0008	0.0020	0.0104	0.9480	0.0388	0.0008	0.0020	0.0100	0.0200	0.9000	0.0676	0.0024	0.0004	0.0008	0.0104	0.9096	0.0788	-	0.0008	0.0112	0.0408	0.9472
98.50	19	at t = 0.95 T	0.9000	0.0987	0.0003	0.0003	0.0007	0.0102	0.9493	0.0396	0.0003	0.0007	0.0100	0.0200	0.9000	0.0691	0.0009	0.0002	0.0003	0.0102	0.9099	0.0796	-	0.0003	0.0105	0.0403	0.9490
100.00	20	at t = 1.00 T	**0.9000**	**0.1000**	-	-	-	**0.0100**	**0.9500**	**0.0400**	-	-	**0.0100**	**0.0200**	**0.9000**	**0.0700**	-	-	-	**0.0100**	**0.9100**	**0.0800**	-	-	**0.0100**	**0.0400**	**0.9500**


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Safety Forecasting Model

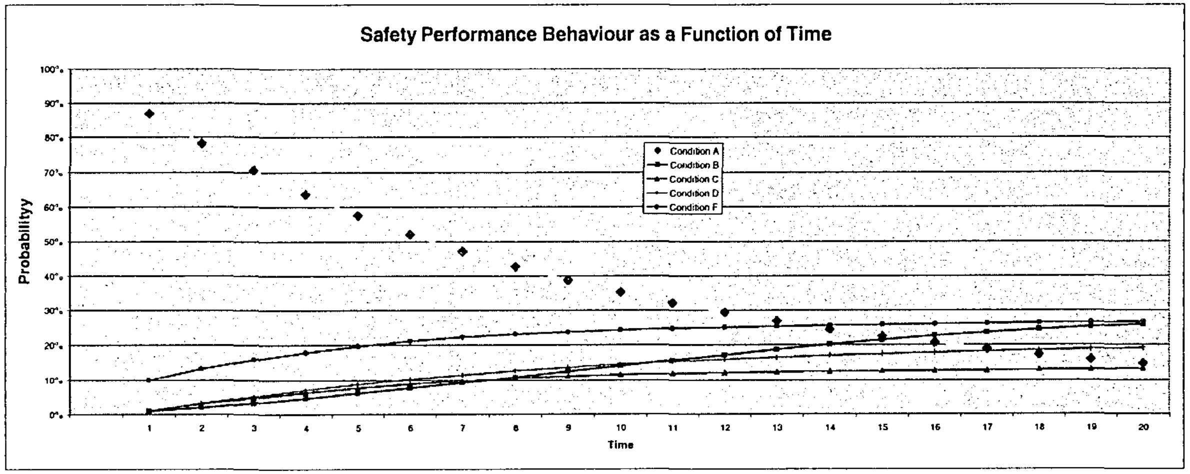
	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						0.9000	0.0100	0.0200	0.0200	0.0500	0.9000	0.0145	0.0190	0.0190	0.0475	0.9000	0.0177	0.0183	0.0183	0.0458	0.9000	0.0213	0.0175	0.0175	0.0438
B						0.0200	0.9000	0.0100	0.0200	0.0500	0.0195	0.9025	0.0115	0.0190	0.0475	0.0192	0.9043	0.0126	0.0183	0.0458	0.0188	0.9063	0.0138	0.0175	0.0438
C						0.0100	0.0200	0.9000	0.0100	0.0600	0.0100	0.0200	0.9000	0.0130	0.0570	0.0100	0.0200	0.9000	0.0151	0.0549	0.0100	0.0200	0.9000	0.0175	0.0525
D						0.0100	0.0200	0.0200	0.9000	0.0500	0.0095	0.0190	0.0195	0.9005	0.0515	0.0092	0.0183	0.0192	0.9009	0.0526	0.0088	0.0175	0.0188	0.9013	0.0538
F						-	0.0200	0.0400	0.0600	0.8800	-	0.0190	0.0385	0.0590	0.8835	-	0.0183	0.0375	0.0583	0.8860	-	0.0175	0.0363	0.0575	0.8888

	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.9000	0.0253	0.0166	0.0166	0.0415	0.9000	0.0302	0.0155	0.0155	0.0388	0.9000	0.0365	0.0141	0.0141	0.0353	0.9000	0.0432	0.0126	0.0126	0.0315	0.9000	0.0504	0.0110	0.0110	0.0275
B	0.0183	0.9085	0.0151	0.0166	0.0415	0.0178	0.9112	0.0167	0.0155	0.0388	0.0171	0.9147	0.0188	0.0141	0.0353	0.0163	0.9185	0.0211	0.0126	0.0315	0.0155	0.9225	0.0235	0.0110	0.0275
C	0.0100	0.0200	0.9000	0.0202	0.0498	0.0100	0.0200	0.9000	0.0235	0.0465	0.0100	0.0200	0.9000	0.0277	0.0423	0.0100	0.0200	0.9000	0.0322	0.0378	0.0100	0.0200	0.9000	0.0370	0.0330
D	0.0083	0.0166	0.0183	0.9017	0.0551	0.0078	0.0155	0.0178	0.9022	0.0567	0.0071	0.0141	0.0171	0.9029	0.0588	0.0063	0.0126	0.0163	0.9037	0.0611	0.0055	0.0110	0.0155	0.9045	0.0635
F	-	0.0166	0.0349	0.0566	0.8919	-	0.0155	0.0333	0.0555	0.8957	-	0.0141	0.0312	0.0541	0.9006	-	0.0126	0.0289	0.0526	0.9059	-	0.0110	0.0265	0.0510	0.9115

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.9000	0.0576	0.0094	0.0094	0.0235	0.9000	0.0648	0.0078	0.0078	0.0195	0.9000	0.0717	0.0063	0.0063	0.0158	0.9000	0.0784	0.0048	0.0048	0.0120	0.9000	0.0847	0.0034	0.0034	0.0085
B	0.0147	0.9265	0.0259	0.0094	0.0235	0.0139	0.9305	0.0283	0.0078	0.0195	0.0132	0.9343	0.0306	0.0063	0.0158	0.0124	0.9380	0.0328	0.0048	0.0120	0.0117	0.9415	0.0349	0.0034	0.0085
C	0.0100	0.0200	0.9000	0.0418	0.0282	0.0100	0.0200	0.9000	0.0466	0.0234	0.0100	0.0200	0.9000	0.0511	0.0189	0.0100	0.0200	0.9000	0.0556	0.0144	0.0100	0.0200	0.9000	0.0598	0.0102
D	0.0047	0.0094	0.0147	0.9053	0.0659	0.0039	0.0078	0.0139	0.9061	0.0683	0.0032	0.0063	0.0132	0.9069	0.0706	0.0024	0.0048	0.0124	0.9076	0.0728	0.0017	0.0034	0.0117	0.9083	0.0749
F	-	0.0094	0.0241	0.0494	0.9171	-	0.0078	0.0217	0.0478	0.9227	-	0.0063	0.0195	0.0463	0.9280	-	0.0048	0.0172	0.0448	0.9332	-	0.0034	0.0151	0.0434	0.9381

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.9000	0.0906	0.0021	0.0021	0.0053	0.9000	0.0942	0.0013	0.0013	0.0033	0.9000	0.0964	0.0008	0.0008	0.0020	0.9000	0.0987	0.0003	0.0003	0.0007	0.9000	0.1000	-	-	-
B	0.0111	0.9448	0.0369	0.0021	0.0053	0.0107	0.9468	0.0381	0.0013	0.0033	0.0104	0.9480	0.0388	0.0008	0.0020	0.0102	0.9493	0.0396	0.0003	0.0007	0.0100	0.9500	0.0400	-	-
C	0.0100	0.0200	0.9000	0.0637	0.0063	0.0100	0.0200	0.9000	0.0661	0.0039	0.0100	0.0200	0.9000	0.0676	0.0024	0.0100	0.0200	0.9000	0.0691	0.0009	0.0100	0.0200	0.9000	0.0700	-
D	0.0011	0.0021	0.0111	0.9090	0.0769	0.0007	0.0013	0.0107	0.9094	0.0781	0.0004	0.0008	0.0104	0.9096	0.0788	0.0002	0.0003	0.0102	0.9099	0.0796	-	-	0.0100	0.9100	0.0800
F	-	0.0021	0.0132	0.0421	0.9427	-	0.0013	0.0120	0.0413	0.9455	-	0.0008	0.0112	0.0408	0.9472	-	0.0003	0.0105	0.0403	0.9490	-	-	0.0100	0.0400	0.9500

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Safety Index	Expected Value	The expected safety performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80	at t = 0.85	at t = 0.90	at t = 0.95	at t = 1.00 T			
	CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probab	State Proba	State Proba	State Proba	State Prob	State Proba	State Proba	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	SFI	SFI	
	A		87%	78.34%	70.61%	63.71%	57.55%	52.06%	47.16%	42.78%	38.87%	35.36%	32.22%	29.39%	26.85%	24.56%	22.50%	20.63%	18.95%	17.43%	16.07%	14.85%	1.20	0.18	
	B		1%	2.01%	3.33%	4.74%	6.22%	7.73%	9.28%	10.88%	12.51%	14.13%	15.73%	17.28%	18.75%	20.14%	21.44%	22.64%	23.69%	24.57%	25.32%	25.92%	1.10	0.29	
Initial Probability Vector obtained from company historic records	C		1%	3.07%	4.85%	6.40%	7.72%	8.85%	9.79%	10.54%	11.13%	11.58%	11.92%	12.18%	12.37%	12.52%	12.65%	12.75%	12.87%	13.00%	13.14%	13.29%	1.00	0.13	
	D		1%	3.27%	5.30%	7.13%	8.77%	10.24%	11.55%	12.69%	13.70%	14.59%	15.36%	16.03%	16.62%	17.13%	17.57%	17.96%	18.30%	18.62%	18.92%	19.19%	0.90	0.17	98.30%
	F		10%	13.31%	15.92%	18.03%	19.74%	21.12%	22.23%	23.10%	23.79%	24.34%	24.77%	25.12%	25.41%	25.65%	25.85%	26.03%	26.20%	26.37%	26.55%	26.74%	0.80	0.21	or Within TARGET
	sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	0.983	
			1.15	1.13	1.11	1.09	1.07	1.06	1.05	1.04	1.03	1.02	1.02	1.01	1.01	1.00	1.00	0.99	0.99	0.99	0.99	0.98			



APPENDIX (J)

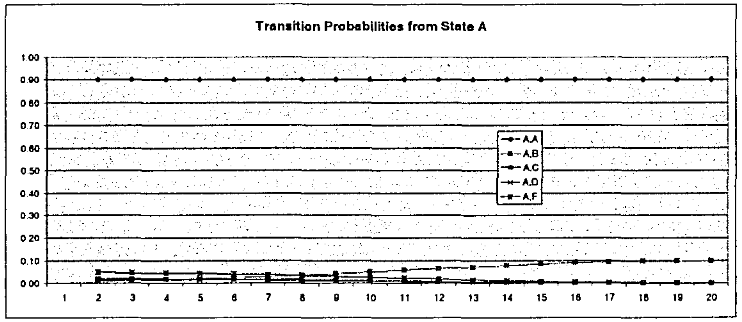
Forecasting Project Performance using Dynamic Markov Chains

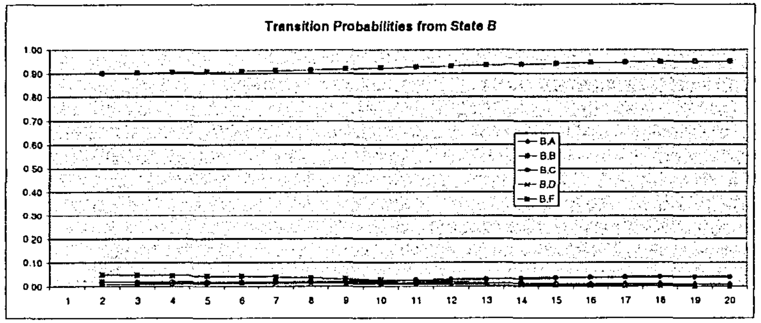
Safety Forecasting Update

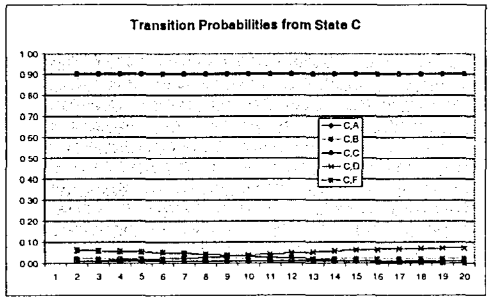
Transition Probabilities as a Function of Project Duration (T)

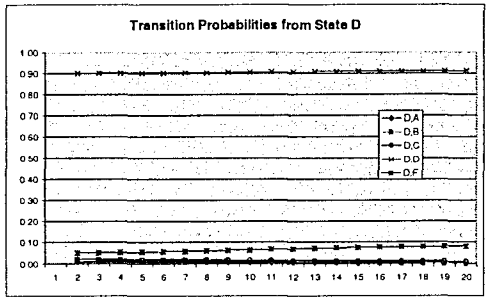
boundary conditions derived based on company historic database

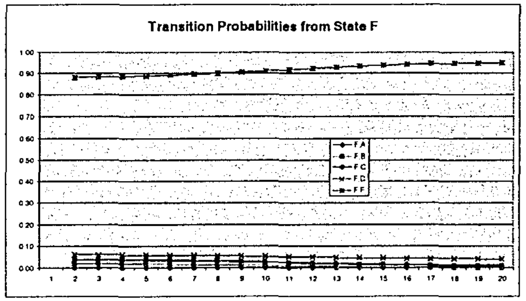
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t ≈ 0.05 T																									
2.50	2	at t ≈ 0.10 T	**0.9000**	**0.0100**	**0.0200**	**0.0200**	**0.0500**	**0.0200**	**0.9000**	**0.0100**	**0.0200**	**0.0500**	**0.0100**	**0.0200**	**0.9000**	**0.0100**	**0.0600**	**0.0100**	**0.0200**	**0.0200**	**0.9000**	**0.0500**	-	**0.0200**	**0.0400**	**0.0600**	**0.8800**
5.00	3	at t ≈ 0.15 T	0.9000	0.0145	0.0190	0.0190	0.0475	0.0195	0.9025	0.0115	0.0190	0.0475	0.0100	0.0200	0.9000	0.0130	0.0570	0.0095	0.0190	0.0195	0.9005	0.0515	-	0.0190	0.0385	0.0590	0.8835
8.50	4	at t ≈ 0.20 T	0.9000	0.0177	0.0183	0.0183	0.0458	0.0192	0.9043	0.0126	0.0183	0.0458	0.0100	0.0200	0.9000	0.0151	0.0549	0.0092	0.0183	0.0192	0.9009	0.0526	-	0.0183	0.0375	0.0583	0.8860
12.50	5	at t ≈ 0.25 T	0.9000	0.0213	0.0175	0.0175	0.0438	0.0188	0.9063	0.0138	0.0175	0.0438	0.0100	0.0200	0.9000	0.0175	0.0525	0.0088	0.0175	0.0188	0.9013	0.0538	-	0.0175	0.0363	0.0575	0.8888
17.00	6	at t ≈ 0.30 T	0.9000	0.0253	0.0166	0.0166	0.0415	0.0183	0.9085	0.0151	0.0166	0.0415	0.0100	0.0200	0.9000	0.0202	0.0498	0.0083	0.0166	0.0183	0.9017	0.0551	-	0.0166	0.0349	0.0566	0.8919
22.43	7	at t ≈ 0.35 T	0.9000	0.0302	0.0155	0.0155	0.0388	0.0178	0.9112	0.0167	0.0155	0.0388	0.0100	0.0200	0.9000	0.0235	0.0465	0.0078	0.0155	0.0178	0.9022	0.0567	-	0.0155	0.0333	0.0555	0.8957
29.43	8	at t ≈ 0.40 T	0.9000	0.0365	0.0141	0.0141	0.0353	0.0171	0.9147	0.0188	0.0141	0.0353	0.0100	0.0200	0.9000	0.0277	0.0423	0.0071	0.0141	0.0171	0.9029	0.0588	-	0.0141	0.0312	0.0541	0.9006
36.93	9	at t ≈ 0.45 T	0.9000	0.0432	0.0126	0.0126	0.0315	0.0163	0.9185	0.0211	0.0126	0.0315	0.0100	0.0200	0.9000	0.0322	0.0378	0.0063	0.0126	0.0163	0.9037	0.0611	-	0.0126	0.0289	0.0526	0.9059
44.93	10	at t ≈ 0.50 T	0.9000	0.0504	0.0110	0.0110	0.0275	0.0155	0.9225	0.0235	0.0110	0.0275	0.0100	0.0200	0.9000	0.0370	0.0330	0.0055	0.0110	0.0155	0.9045	0.0635	-	0.0110	0.0265	0.0510	0.9115
52.93	11	at t ≈ 0.55 T	0.9000	0.0576	0.0094	0.0094	0.0235	0.0147	0.9265	0.0259	0.0094	0.0235	0.0100	0.0200	0.9000	0.0418	0.0282	0.0047	0.0094	0.0147	0.9053	0.0659	-	0.0094	0.0241	0.0494	0.9171
60.93	12	at t ≈ 0.60 T	0.9000	0.0648	0.0078	0.0078	0.0195	0.0139	0.9305	0.0283	0.0078	0.0195	0.0100	0.0200	0.9000	0.0466	0.0234	0.0039	0.0078	0.0139	0.9061	0.0683	-	0.0078	0.0217	0.0478	0.9227
68.50	13	at t ≈ 0.65 T	0.9000	0.0717	0.0063	0.0063	0.0158	0.0132	0.9343	0.0306	0.0063	0.0158	0.0100	0.0200	0.9000	0.0511	0.0189	0.0032	0.0063	0.0132	0.9069	0.0706	-	0.0063	0.0195	0.0463	0.9280
76.00	14	at t ≈ 0.70 T	0.9000	0.0784	0.0048	0.0048	0.0120	0.0124	0.9380	0.0328	0.0048	0.0120	0.0100	0.0200	0.9000	0.0556	0.0144	0.0024	0.0048	0.0124	0.9076	*0.0728*	-	*0.0048*	*0.0172*	*0.0448*	*0.9332*
83.00	15	at t ≈ 0.75 T	0.9000	0.0847	0.0034	0.0034	0.0085	0.0117	0.9415	0.0349	0.0034	0.0085	0.0100	0.0200	0.9000	0.0598	0.0102	0.0017	0.0034	0.0117	0.9083	0.0749	-	0.0034	0.0151	0.0434	0.9381
89.50	16	at t ≈ 0.80 T	0.9000	0.0906	0.0021	0.0021	0.0053	0.0111	0.9448	0.0369	0.0021	0.0053	0.0100	0.0200	0.9000	0.0637	0.0063	0.0011	0.0021	0.0111	0.9090	0.0769	-	0.0021	0.0132	0.0421	0.9427
93.50	17	at t ≈ 0.85 T	0.9000	0.0942	0.0013	0.0013	0.0033	0.0107	0.9468	0.0381	0.0013	0.0033	0.0100	0.0200	0.9000	0.0661	0.0039	0.0007	0.0013	0.0107	0.9094	0.0781	-	0.0013	0.0120	0.0413	0.9455
96.00	18	at t ≈ 0.90 T	0.9000	0.0964	0.0008	0.0008	0.0020	0.0104	0.9480	0.0388	0.0008	0.0020	0.0100	0.0200	0.9000	0.0676	0.0024	0.0004	0.0008	0.0104	0.9096	0.0788	-	0.0008	0.0112	0.0408	0.9472
98.50	19	at t ≈ 0.95 T	0.9000	0.0987	0.0003	0.0003	0.0007	0.0102	0.9493	0.0396	0.0003	0.0007	0.0100	0.0200	0.9000	0.0691	0.0009	0.0002	0.0003	0.0102	0.9099	0.0796	-	0.0003	0.0105	0.0403	0.9490
100.00	20	at t ≈ 1.00 T	**0.9000**	**0.1000**	-	-	-	**0.0100**	**0.9500**	**0.0400**	-	-	**0.0100**	**0.0200**	**0.9000**	**0.0700**	-	-	-	**0.0100**	**0.9100**	**0.0800**	-	-	**0.0100**	**0.0400**	**0.9500**


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Safety Forecasting Update

at t = 0.05 T

	A	B	C	D	F
A					
B					
C					
D					
F					

at t = 0.10 T

	A	B	C	D	F
A	**0.9000**	**0.0100**	**0.0200**	**0.0200**	**0.0500**
B	**0.0200**	**0.9000**	**0.0100**	**0.0200**	**0.0500**
C	**0.0100**	**0.0200**	**0.9000**	**0.0100**	**0.0600**
D	**0.0100**	**0.0200**	**0.0200**	**0.9000**	**0.0500**
F	**-**	**0.0200**	**0.0400**	**0.0600**	**0.8800**

at t = 0.15 T

	A	B	C	D	F
A	0.9000	0.0145	0.0190	0.0190	0.0475
B	0.0195	0.9025	0.0115	0.0190	0.0475
C	0.0100	0.0200	0.9000	0.0130	0.0570
D	0.0095	0.0190	0.0195	0.9005	0.0515
F	-	0.0190	0.0385	0.0590	0.8835

at t = 0.20 T

	A	B	C	D	F
A	0.9000	0.0177	0.0183	0.0183	0.0458
B	0.0192	0.9043	0.0126	0.0183	0.0458
C	0.0100	0.0200	0.9000	0.0151	0.0549
D	0.0092	0.0183	0.0192	0.9009	0.0526
F	-	0.0183	0.0375	0.0583	0.8860

at t = 0.25 T

	A	B	C	D	F
A	0.9000	0.0213	0.0175	0.0175	0.0438
B	0.0188	0.9063	0.0138	0.0175	0.0438
C	0.0100	0.0200	0.9000	0.0175	0.0525
D	0.0088	0.0175	0.0188	0.9013	0.0538
F	-	0.0175	0.0363	0.0575	0.8888

at t = 0.30 T

	A	B	C	D	F
A	0.9000	0.0253	0.0166	0.0166	0.0415
B	0.0183	0.9085	0.0151	0.0166	0.0415
C	0.0100	0.0200	0.9000	0.0202	0.0498
D	0.0083	0.0166	0.0183	0.9017	0.0551
F	-	0.0166	0.0349	0.0566	0.8919

at t = 0.35 T

	A	B	C	D	F
A	0.9000	0.0302	0.0155	0.0155	0.0388
B	0.0178	0.9112	0.0167	0.0155	0.0388
C	0.0100	0.0200	0.9000	0.0235	0.0465
D	0.0078	0.0155	0.0178	0.9022	0.0567
F	-	0.0155	0.0333	0.0555	0.8957

at t = 0.40 T

	A	B	C	D	F
A	0.9000	0.0365	0.0141	0.0141	0.0353
B	0.0171	0.9147	0.0188	0.0141	0.0353
C	0.0100	0.0200	0.9000	0.0277	0.0423
D	0.0071	0.0141	0.0171	0.9029	0.0588
F	-	0.0141	0.0312	0.0541	0.9006

at t = 0.45 T

	A	B	C	D	F
A	0.9000	0.0432	0.0126	0.0126	0.0315
B	0.0163	0.9185	0.0211	0.0126	0.0315
C	0.0100	0.0200	0.9000	0.0322	0.0378
D	0.0063	0.0126	0.0163	0.9037	0.0611
F	-	0.0126	0.0289	0.0526	0.9059

at t = 0.50 T

	A	B	C	D	F
A	0.9000	0.0504	0.0110	0.0110	0.0275
B	0.0155	0.9225	0.0235	0.0110	0.0275
C	0.0100	0.0200	0.9000	0.0370	0.0330
D	0.0055	0.0110	0.0155	0.9045	0.0635
F	-	0.0110	0.0265	0.0510	0.9115

at t = 0.55 T

	A	B	C	D	F
A	0.9000	0.0576	0.0094	0.0094	0.0235
B	0.0147	0.9265	0.0259	0.0094	0.0235
C	0.0100	0.0200	0.9000	0.0418	0.0282
D	0.0047	0.0094	0.0147	0.9053	0.0659
F	-	0.0094	0.0241	0.0494	0.9171

at t = 0.60 T

	A	B	C	D	F
A	0.9000	0.0648	0.0078	0.0078	0.0195
B	0.0139	0.9305	0.0283	0.0078	0.0195
C	0.0100	0.0200	0.9000	0.0466	0.0234
D	0.0039	0.0078	0.0139	0.9061	0.0683
F	-	0.0078	0.0217	0.0478	0.9227

at t = 0.65 T

	A	B	C	D	F
A	0.9000	0.0717	0.0063	0.0063	0.0158
B	0.0132	0.9343	0.0306	0.0063	0.0158
C	0.0100	0.0200	0.9000	0.0511	0.0189
D	0.0032	0.0063	0.0132	0.9069	0.0706
F	-	0.0063	0.0195	0.0463	0.9280

at t = 0.70 T

	A	B	C	D	F
A	0.9000	0.0784	0.0048	0.0048	0.0120
B	0.0124	0.9380	0.0328	0.0048	0.0120
C	0.0100	0.0200	0.9000	0.0556	0.0144
D	0.0024	0.0048	0.0124	0.9076	0.0728
F	-	0.0048	0.0172	0.0448	0.9332

at t = 0.75 T

	A	B	C	D	F
A	0.9000	0.0847	0.0034	0.0034	0.0085
B	0.0117	0.9415	0.0349	0.0034	0.0085
C	0.0100	0.0200	0.9000	0.0598	0.0102
D	0.0017	0.0034	0.0117	0.9083	0.0749
F	-	0.0034	0.0151	0.0434	0.9381

at t = 0.80 T

	A	B	C	D	F
A	0.9000	0.0906	0.0021	0.0021	0.0053
B	0.0111	0.9448	0.0369	0.0021	0.0053
C	0.0100	0.0200	0.9000	0.0637	0.0063
D	0.0011	0.0021	0.0111	0.9090	0.0769
F	-	0.0021	0.0132	0.0421	0.9427

at t = 0.85 T

	A	B	C	D	F
A	0.9000	0.0942	0.0013	0.0013	0.0033
B	0.0107	0.9468	0.0381	0.0013	0.0033
C	0.0100	0.0200	0.9000	0.0661	0.0039
D	0.0007	0.0013	0.0107	0.9094	0.0781
F	-	0.0013	0.0120	0.0413	0.9455

at t = 0.90 T

	A	B	C	D	F
A	0.9000	0.0964	0.0008	0.0008	0.0020
B	0.0104	0.9480	0.0388	0.0008	0.0020
C	0.0100	0.0200	0.9000	0.0676	0.0024
D	0.0004	0.0008	0.0104	0.9096	0.0788
F	-	0.0008	0.0112	0.0408	0.9472

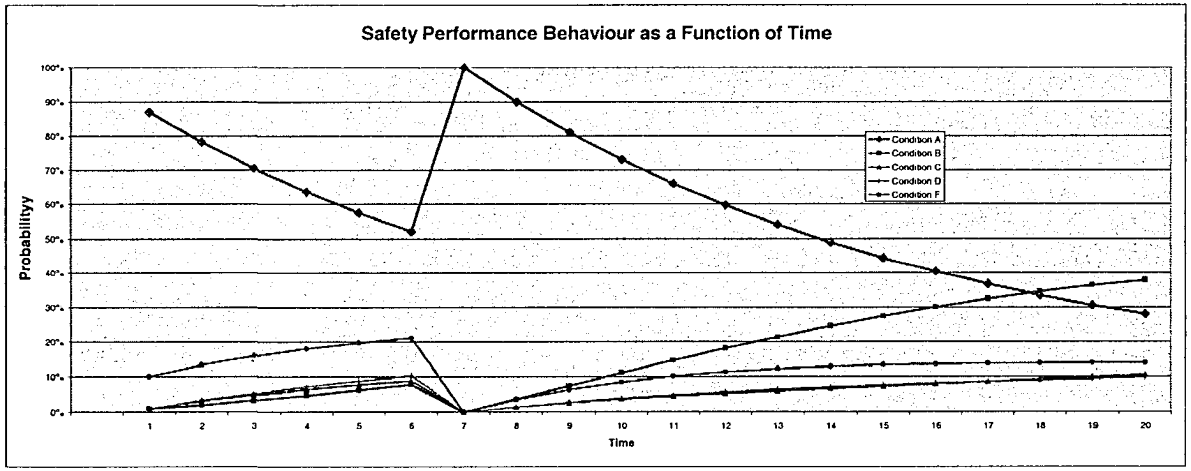
at t = 0.95 T

	A	B	C	D	F
A	0.9000	0.0987	0.0003	0.0003	0.0007
B	0.0102	0.9493	0.0396	0.0003	0.0007
C	0.0100	0.0200	0.9000	0.0691	0.0009
D	0.0002	0.0003	0.0102	0.9099	0.0796
F	-	0.0003	0.0105	0.0403	0.9490

at t = 1.00 T

	A	B	C	D	F
A	**0.9000**	**0.1000**	-	-	-
B	**0.0100**	**0.9500**	**0.0400**	-	-
C	**0.0100**	**0.0200**	**0.9000**	**0.0700**	-
D	-	-	**0.0100**	**0.9100**	**0.0800**
F	-	-	**0.0100**	**0.0400**	**0.9500**

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Safety Index	Expected Value	The expected safety performance at the end of the project given the latest actual status is equal to :
			at t = 0.05	at t = 0.10	at t = 0.15	at t = 0.20	at t = 0.25 T	at t = 0.30	at t = 0.35	at t = 0.40	at t = 0.45	at t = 0.50	at t = 0.55	at t = 0.60	at t = 0.65	at t = 0.70	at t = 0.75	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00			
	CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probal	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Pro	State Pro	State Pro	State Pro	State Proba	SFI	SFI	
	A		87%	78.34%	70.61%	63.71%	57.55%	52.06%	**100.00%**	90.00%	81.08%	**73.13%**	**66.03%**	**59.70%**	**54.03%**	**48.97%**	**44.44%**	40.38%	36.74%	33.50%	30.59%	27.99%	1.20	0.34	
	B		1%	2.01%	3.33%	4.74%	6.22%	7.73%	0.00%	3.65%	7.33%	**11.01%**	**14.60%**	**18.07%**	**21.37%**	**24.49%**	**27.41%**	30.11%	32.49%	34.53%	36.27%	37.72%	1.10	0.41	
Initial Probability Vector obtained from company historic records	C		1%	3.07%	4.85%	6.40%	7.72%	8.85%	0.00%	1.41%	2.61%	**3.62%**	**4.49%**	**5.26%**	**5.95%**	**6.61%**	**7.25%**	7.88%	8.54%	9.22%	9.91%	10.60%	1.00	0.11	
	D		1%	3.27%	5.30%	7.13%	8.77%	10.24%	0.00%	1.41%	2.69%	**3.82%**	**4.82%**	**5.69%**	**6.44%**	**7.08%**	**7.64%**	8.11%	8.55%	8.97%	9.37%	9.78%	0.90	0.09	**105.61%**
	F		10%	13.31%	15.92%	18.03%	19.74%	21.12%	0.00%	3.53%	6.29%	**8.42%**	**10.06%**	**11.29%**	**12.20%**	**12.85%**	**13.27%**	13.52%	13.68%	13.79%	13.86%	13.91%	0.80	0.11	or Exceeds TARGET
	sum		**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	Total	1.056	
			1.15	1.13	1.11	1.09	1.07	1.06	1.20	1.18	1.15	1.14	1.12	1.11	1.10	1.09	1.08	1.08	1.07	1.06	1.06	1.06			


Safety Performance Behaviour as a Function of Time

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

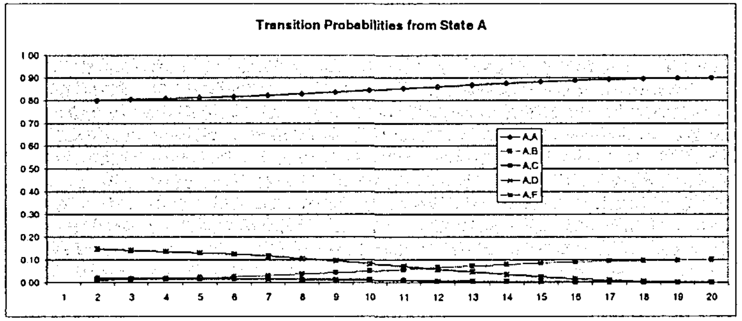
Safety Forecasting Update - Scenario 1

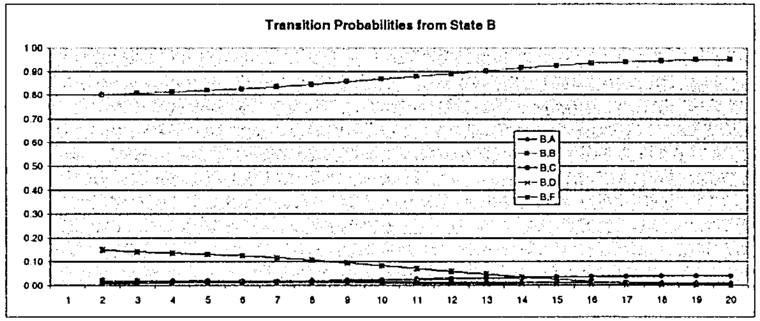
Changes in Boundary Conditions

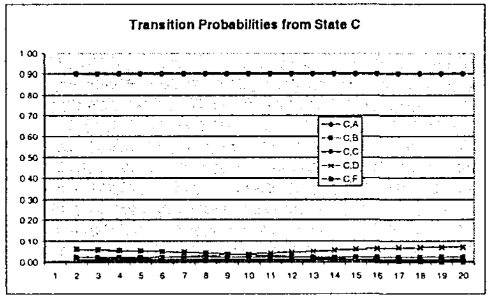
Transition Probabilities as a Function of Project Duration (T)

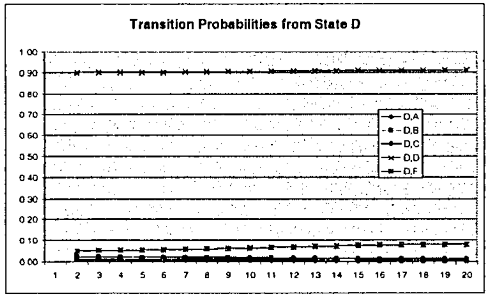
boundary conditions derived based on company historic database

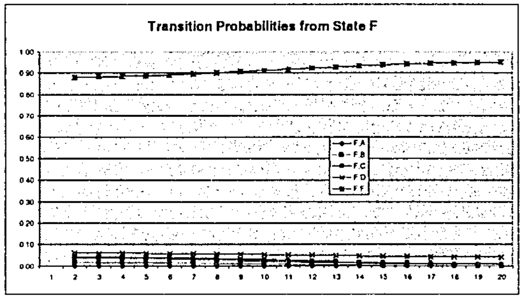
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	**0.8000**	**0.0100**	**0.0200**	**0.0200**	**0.1500**	**0.0200**	**0.8000**	**0.0100**	**0.0200**	**0.1500**	**0.0100**	**0.0200**	**0.9000**	**0.0100**	**0.0600**	**0.0100**	**0.0200**	**0.0200**	**0.9000**	**0.0500**	-	**0.0200**	**0.0400**	**0.0600**	**0.8800**
5.00	3	at t = 0.15 T	0.8050	0.0145	0.0190	0.0190	0.1425	0.0195	0.8075	0.0115	0.0190	0.1425	0.0100	0.0200	0.9000	0.0130	0.0570	0.0095	0.0190	0.0195	0.9005	0.0515	-	0.0190	0.0385	0.0590	0.8835
8.50	4	at t = 0.20 T	0.8085	0.0177	0.0183	0.0183	0.1373	0.0192	0.8128	0.0126	0.0183	0.1373	0.0100	0.0200	0.9000	0.0151	0.0549	0.0092	0.0183	0.0192	0.9009	0.0526	-	0.0183	0.0375	0.0583	0.8860
12.50	5	at t = 0.25 T	0.8125	0.0213	0.0175	0.0175	0.1313	0.0188	0.8188	0.0138	0.0175	0.1313	0.0100	0.0200	0.9000	0.0175	0.0525	0.0088	0.0175	0.0188	0.9013	0.0538	-	0.0175	0.0363	0.0575	0.8888
17.00	6	at t = 0.30 T	0.8170	0.0253	0.0166	0.0166	0.1245	0.0183	0.8255	0.0151	0.0166	0.1245	0.0100	0.0200	0.9000	0.0202	0.0498	0.0083	0.0166	0.0183	0.9017	0.0551	-	0.0166	0.0349	0.0566	0.8919
22.43	7	at t = 0.35 T	0.8224	0.0302	0.0155	0.0155	0.1164	0.0178	0.8336	0.0167	0.0155	0.1164	0.0100	0.0200	0.9000	0.0235	0.0465	0.0078	0.0155	0.0178	0.9022	0.0567	-	0.0155	0.0333	0.0555	0.8957
29.43	8	at t = 0.40 T	0.8294	0.0365	0.0141	0.0141	0.1059	0.0171	0.8441	0.0188	0.0141	0.1059	0.0100	0.0200	0.9000	0.0277	0.0423	0.0071	0.0141	0.0171	0.9029	0.0588	-	0.0141	0.0312	0.0541	0.9006
36.93	9	at t = 0.45 T	0.8369	0.0432	0.0126	0.0126	0.0946	0.0163	0.8554	0.0211	0.0126	0.0946	0.0100	0.0200	0.9000	0.0322	0.0378	0.0063	0.0126	0.0163	0.9037	0.0611	-	0.0126	0.0289	0.0526	0.9059
44.93	10	at t = 0.50 T	0.8449	0.0504	0.0110	0.0110	0.0826	0.0155	0.8674	0.0235	0.0110	0.0826	0.0100	0.0200	0.9000	0.0370	0.0330	0.0055	0.0110	0.0155	0.9045	0.0635	-	0.0110	0.0265	0.0510	0.9115
52.93	11	at t = 0.55 T	0.8529	0.0576	0.0094	0.0094	0.0706	0.0147	0.8794	0.0259	0.0094	0.0706	0.0100	0.0200	0.9000	0.0418	0.0282	0.0047	0.0094	0.0147	0.9053	0.0659	-	0.0094	0.0241	0.0494	0.9171
60.93	12	at t = 0.60 T	0.8609	0.0648	0.0078	0.0078	0.0586	0.0139	0.8914	0.0283	0.0078	0.0586	0.0100	0.0200	0.9000	0.0466	0.0234	0.0039	0.0078	0.0139	0.9061	0.0683	-	0.0078	0.0217	0.0478	0.9227
68.50	13	at t = 0.65 T	0.8685	0.0717	0.0063	0.0063	0.0473	0.0132	0.9028	0.0306	0.0063	0.0473	0.0100	0.0200	0.9000	0.0511	0.0189	0.0032	0.0063	0.0132	0.9069	0.0706	-	0.0063	0.0195	0.0463	0.9280
76.00	14	at t = 0.70 T	0.8760	0.0784	0.0048	0.0048	0.0360	0.0124	0.9140	0.0328	0.0048	0.0360	0.0100	0.0200	0.9000	0.0556	0.0144	0.0024	0.0048	0.0124	0.9076	0.0728	-	0.0048	0.0172	0.0448	0.9332
83.00	15	at t = 0.75 T	0.8830	0.0847	0.0034	0.0034	0.0255	0.0117	0.9245	0.0349	0.0034	0.0255	0.0100	0.0200	0.9000	0.0598	0.0102	0.0017	0.0034	0.0117	0.9083	0.0749	-	0.0034	0.0151	0.0434	0.9381
89.50	16	at t = 0.80 T	0.8895	0.0906	0.0021	0.0021	0.0158	0.0111	0.9343	0.0369	0.0021	0.0158	0.0100	0.0200	0.9000	0.0637	0.0063	0.0011	0.0021	0.0111	0.9090	0.0769	-	0.0021	0.0132	0.0421	0.9427
93.50	17	at t = 0.85 T	0.8935	0.0942	0.0013	0.0013	0.0097	0.0107	0.9403	0.0381	0.0013	0.0097	0.0100	0.0200	0.9000	0.0661	0.0039	0.0007	0.0013	0.0107	0.9094	0.0781	-	0.0013	0.0120	0.0413	0.9455
96.00	18	at t = 0.90 T	0.8960	0.0964	0.0008	0.0008	0.0060	0.0104	0.9440	0.0388	0.0008	0.0060	0.0100	0.0200	0.9000	0.0676	0.0024	0.0004	0.0008	0.0104	0.9096	0.0788	-	0.0008	0.0112	0.0408	0.9472
98.50	19	at t = 0.95 T	0.8985	0.0987	0.0003	0.0003	0.0023	0.0102	0.9478	0.0396	0.0003	0.0023	0.0100	0.0200	0.9000	0.0691	0.0009	0.0002	0.0003	0.0102	0.9099	0.0796	-	0.0003	0.0105	0.0403	0.9490
100.00	20	at t = 1.00 T	**0.9000**	**0.1000**	-	-	-	**0.0100**	**0.9500**	**0.0400**	-	-	**0.0100**	**0.0200**	**0.9000**	**0.0700**	-	-	-	**0.0100**	**0.9100**	**0.0800**	-	-	**0.0100**	**0.0400**	**0.9500**


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Safety Forecasting Update - Scenario 1

Changes in Boundary Conditions

at t = 0.05 T

	A	B	C	D	F
A					
B					
C					
D					
F					

at t = 0.10 T

	A	B	C	D	F
A	**0.8000**	**0.0100**	**0.0200**	**0.0200**	**0.1500**
B	**0.0200**	**0.8000**	**0.0100**	**0.0200**	**0.1500**
C	**0.0100**	**0.0200**	**0.9000**	**0.0100**	**0.0600**
D	**0.0100**	**0.0200**	**0.0200**	**0.9000**	**0.0500**
F	-	**0.0200**	**0.0400**	**0.0600**	**0.8800**

at t = 0.15 T

	A	B	C	D	F
A	0.8050	0.0145	0.0190	0.0190	0.1425
B	0.0195	0.8075	0.0115	0.0190	0.1425
C	0.0100	0.0200	0.9000	0.0130	0.0570
D	0.0095	0.0190	0.0195	0.9005	0.0515
F	-	0.0190	0.0385	0.0590	0.8835

at t = 0.20 T

	A	B	C	D	F
A	0.8085	0.0177	0.0183	0.0183	0.1373
B	0.0192	0.8128	0.0126	0.0183	0.1373
C	0.0100	0.0200	0.9000	0.0151	0.0549
D	0.0092	0.0183	0.0192	0.9009	0.0526
F	-	0.0183	0.0375	0.0583	0.8860

at t = 0.25 T

	A	B	C	D	F
A	0.8125	0.0213	0.0175	0.0175	0.1313
B	0.0188	0.8188	0.0138	0.0175	0.1313
C	0.0100	0.0200	0.9000	0.0175	0.0525
D	0.0088	0.0175	0.0188	0.9013	0.0538
F	-	0.0175	0.0363	0.0575	0.8888

at t = 0.30 T

	A	B	C	D	F
A	0.8170	0.0253	0.0166	0.0166	0.1245
B	0.0183	0.8255	0.0151	0.0166	0.1245
C	0.0100	0.0200	0.9000	0.0202	0.0498
D	0.0083	0.0166	0.0183	0.9017	0.0551
F	-	0.0166	0.0349	0.0566	0.8919

at t = 0.35 T

	A	B	C	D	F
A	0.8224	0.0302	0.0155	0.0155	0.1164
B	0.0178	0.8336	0.0167	0.0155	0.1164
C	0.0100	0.0200	0.9000	0.0235	0.0465
D	0.0078	0.0155	0.0178	0.9022	0.0567
F	-	0.0155	0.0333	0.0555	0.8957

at t = 0.40 T

	A	B	C	D	F
A	0.8294	0.0365	0.0141	0.0141	0.1059
B	0.0171	0.8441	0.0188	0.0141	0.1059
C	0.0100	0.0200	0.9000	0.0277	0.0423
D	0.0071	0.0141	0.0171	0.9029	0.0588
F	-	0.0141	0.0312	0.0541	0.9006

at t = 0.45 T

	A	B	C	D	F
A	0.8369	0.0432	0.0126	0.0126	0.0946
B	0.0163	0.8554	0.0211	0.0126	0.0946
C	0.0100	0.0200	0.9000	0.0322	0.0378
D	0.0063	0.0126	0.0163	0.9037	0.0611
F	-	0.0126	0.0269	0.0526	0.9059

at t = 0.50 T

	A	B	C	D	F
A	0.8449	0.0504	0.0110	0.0110	0.0826
B	0.0155	0.8674	0.0235	0.0110	0.0826
C	0.0100	0.0200	0.9000	0.0370	0.0330
D	0.0055	0.0110	0.0155	0.9045	0.0635
F	-	0.0110	0.0265	0.0510	0.9115

at t = 0.55 T

	A	B	C	D	F
A	0.8529	0.0576	0.0094	0.0094	0.0706
B	0.0147	0.8794	0.0259	0.0094	0.0706
C	0.0100	0.0200	0.9000	0.0418	0.0282
D	0.0047	0.0094	0.0147	0.9053	0.0659
F	-	0.0094	0.0241	0.0494	0.9171

at t = 0.60 T

	A	B	C	D	F
A	0.8609	0.0648	0.0078	0.0078	0.0586
B	0.0139	0.8914	0.0283	0.0078	0.0586
C	0.0100	0.0200	0.9000	0.0466	0.0234
D	0.0039	0.0078	0.0139	0.9061	0.0683
F	-	0.0078	0.0217	0.0478	0.9227

at t = 0.65 T

	A	B	C	D	F
A	0.8685	0.0717	0.0063	0.0063	0.0473
B	0.0132	0.9028	0.0306	0.0063	0.0473
C	0.0100	0.0200	0.9000	0.0511	0.0189
D	0.0032	0.0063	0.0132	0.9069	0.0706
F	-	0.0063	0.0195	0.0463	0.9280

at t = 0.70 T

	A	B	C	D	F
A	0.8760	0.0784	0.0048	0.0048	0.0360
B	0.0124	0.9140	0.0328	0.0048	0.0360
C	0.0100	0.0200	0.9000	0.0556	0.0144
D	0.0024	0.0048	0.0124	0.9076	0.0728
F	-	0.0048	0.0172	0.0448	0.9332

at t = 0.75 T

	A	B	C	D	F
A	0.8830	0.0847	0.0034	0.0034	0.0255
B	0.0117	0.9245	0.0349	0.0034	0.0255
C	0.0100	0.0200	0.9000	0.0598	0.0102
D	0.0017	0.0034	0.0117	0.9083	0.0749
F	-	0.0034	0.0151	0.0434	0.9381

at t = 0.80 T

	A	B	C	D	F
A	0.8895	0.0906	0.0021	0.0021	0.0158
B	0.0111	0.9343	0.0369	0.0021	0.0158
C	0.0100	0.0200	0.9000	0.0637	0.0063
D	0.0011	0.0021	0.0111	0.9090	0.0769
F	-	0.0021	0.0132	0.0421	0.9427

at t = 0.85 T

	A	B	C	D	F
A	0.8935	0.0942	0.0013	0.0013	0.0097
B	0.0107	0.9403	0.0381	0.0013	0.0097
C	0.0100	0.0200	0.9000	0.0661	0.0039
D	0.0007	0.0013	0.0107	0.9094	0.0781
F	-	0.0013	0.0120	0.0413	0.9455

at t = 0.90 T

	A	B	C	D	F
A	0.8960	0.0964	0.0008	0.0008	0.0060
B	0.0104	0.9440	0.0388	0.0008	0.0060
C	0.0100	0.0200	0.9000	0.0676	0.0024
D	0.0004	0.0008	0.0104	0.9096	0.0788
F	-	0.0008	0.0112	0.0408	0.9472

at t = 0.95 T

	A	B	C	D	F
A	0.8985	0.0987	0.0003	0.0003	0.0023
B	0.0102	0.9478	0.0396	0.0003	0.0023
C	0.0100	0.0200	0.9000	0.0691	0.0009
D	0.0002	0.0003	0.0102	0.9099	0.0796
F	-	0.0003	0.0105	0.0403	0.9490

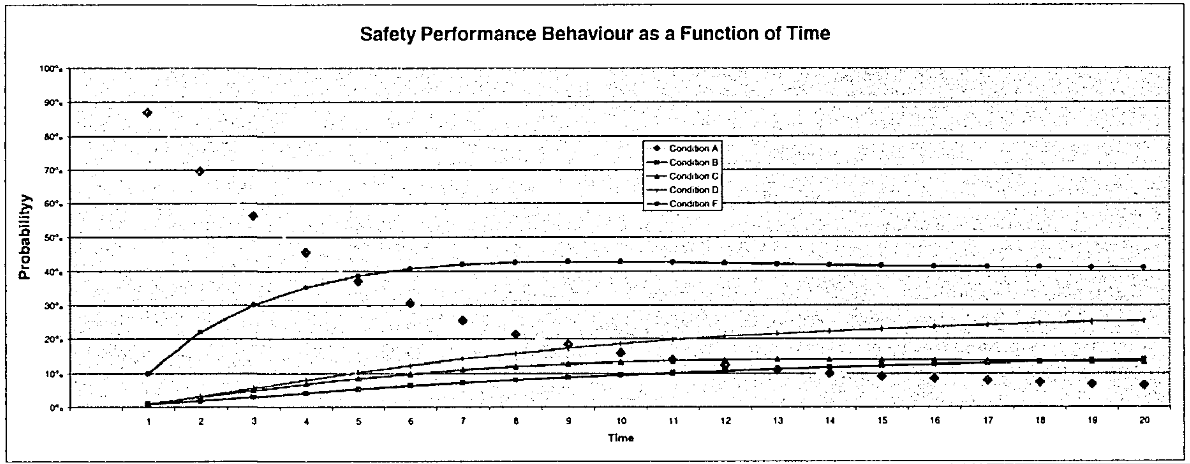
at t = 1.00 T

	A	B	C	D	F
A	**0.9000**	**0.1000**	-	-	-
B	**0.0100**	**0.9500**	**0.0400**	-	-
C	**0.0100**	**0.0200**	**0.9000**	**0.0700**	-
D	-	-	**0.0100**	**0.9100**	**0.0800**
F	-	-	**0.0100**	**0.0400**	**0.9500**

Initial Probability Vector obtained from company historic records

Reporting Period		1	2	3	4	5	6	7	8	9	10
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T
CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probal	State Proba	State Proba	State Proba	State Proba
A		87%	69.64%	56.16%	45.57%	37.24%	30.69%	25.55%	21.52%	18.37%	15.88%
B		1%	1.91%	3.10%	4.26%	5.35%	6.34%	7.23%	8.05%	8.80%	9.47%
C		1%	3.07%	5.02%	6.82%	8.43%	9.82%	11.00%	11.95%	12.69%	13.23%
D		1%	3.27%	5.65%	8.00%	10.24%	12.30%	14.17%	15.84%	17.31%	18.61%
F		10%	22.11%	30.07%	35.35%	38.74%	40.84%	42.05%	42.64%	42.84%	42.81%
sum		**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**
		1.15	1.09	1.05	1.02	0.99	0.97	0.96	0.95	0.94	0.94

Reporting Period	11	12	13	14	15	16	17	18	19	20	Safety Index	Expected Value	
	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00 T			
CONDITION	State Proba	State Proba	State Proba	State Proba	State Proba	State Pro	State Pro	State Pro	State Pro	State Proba	SFI	SFI	The expected safety performance at the end of the project given the latest actual status is equal to :
A	13.90%	12.32%	11.04%	10.00%	9.15%	8.44%	7.82%	7.29%	6.83%	6.41%	1.20	0.08	
B	10.09%	10.65%	11.17%	11.66%	12.13%	12.58%	12.98%	13.33%	13.64%	13.91%	1.10	0.15	
C	13.61%	13.84%	13.96%	13.98%	13.92%	13.79%	13.65%	13.51%	13.37%	13.24%	1.00	0.13	
D	19.76%	20.76%	21.64%	22.42%	23.09%	23.67%	24.18%	24.62%	25.01%	25.34%	0.90	0.23	91.92%
F	42.65%	42.42%	42.18%	41.94%	41.71%	41.52%	41.36%	41.24%	41.15%	41.10%	0.80	0.33	or Below TARGET
sum	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	Total	0.919	
	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.92	0.92	0.92			



APPENDIX (J)

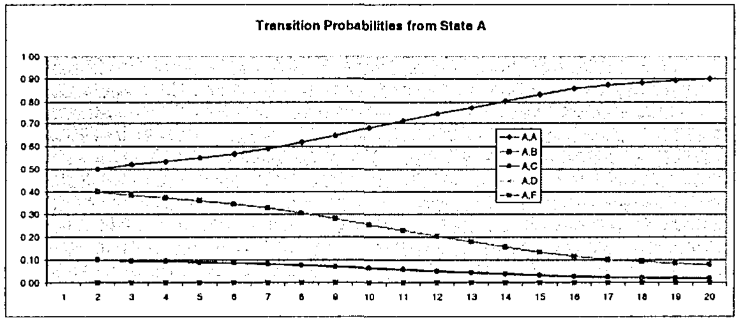
Forecasting Project Performance using Dynamic Markov Chains

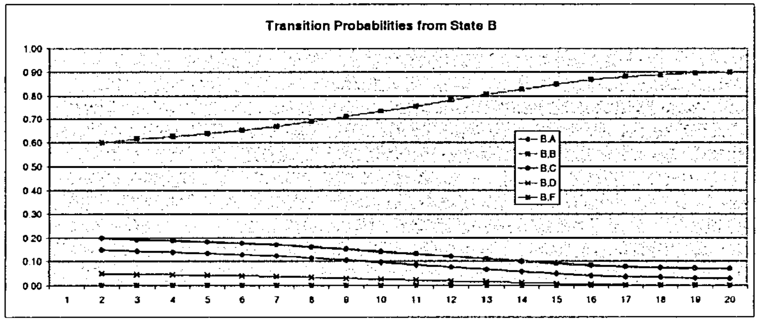
Quality Forecasting Model

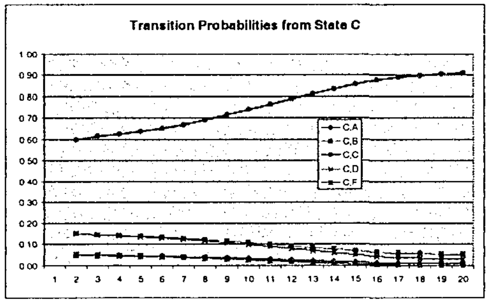
Transition Probabilities as a Function of Project Duration (T)

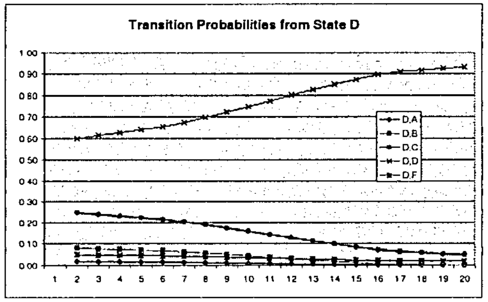
boundary conditions derived based on company historic database

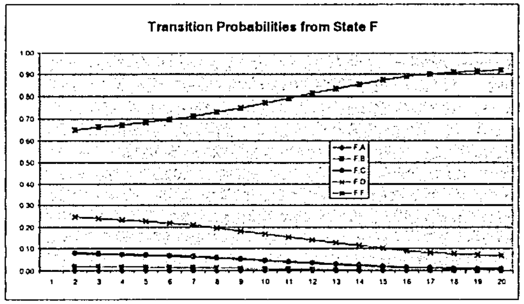
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	**0.5000**	**0.4000**	**0.1000**	-	-	**0.1500**	**0.6000**	**0.2000**	**0.0500**	-	**0.0500**	**0.1500**	**0.6000**	**0.1500**	**0.0500**	**0.0200**	**0.0800**	**0.2500**	**0.6000**	**0.0500**	-	**0.0200**	**0.0800**	**0.2500**	**0.6500**
5.00	3	at t = 0.15 T	0.5200	0.3840	0.0960	-	-	0.1440	0.6150	0.1935	0.0475	-	0.0480	0.1450	0.6155	0.1440	0.0475	0.0190	0.0760	0.2400	0.6165	0.0485	-	0.0190	0.0765	0.2410	0.6635
8.50	4	at t = 0.20 T	0.5340	0.3728	0.0932	-	-	0.1398	0.6255	0.1890	0.0458	-	0.0466	0.1415	0.6264	0.1398	0.0458	0.0183	0.0732	0.2330	0.6281	0.0475	-	0.0183	0.0741	0.2347	0.6730
12.50	5	at t = 0.25 T	0.5500	0.3600	0.0900	-	-	0.1350	0.6375	0.1838	0.0438	-	0.0450	0.1375	0.6388	0.1350	0.0438	0.0175	0.0700	0.2250	0.6413	0.0463	-	0.0175	0.0713	0.2275	0.6838
17.00	6	at t = 0.30 T	0.5680	0.3456	0.0864	-	-	0.1296	0.6510	0.1779	0.0415	-	0.0432	0.1330	0.6527	0.1296	0.0415	0.0166	0.0664	0.2160	0.6561	0.0449	-	0.0166	0.0681	0.2194	0.6959
22.43	7	at t = 0.35 T	0.5897	0.3282	0.0821	-	-	0.1231	0.6673	0.1708	0.0388	-	0.0410	0.1276	0.6695	0.1231	0.0388	0.0155	0.0621	0.2051	0.6740	0.0433	-	0.0155	0.0643	0.2096	0.7106
29.43	8	at t = 0.40 T	0.6177	0.3058	0.0765	-	-	0.1147	0.6883	0.1617	0.0353	-	0.0382	0.1206	0.6912	0.1147	0.0353	0.0141	0.0565	0.1911	0.6971	0.0412	-	0.0141	0.0594	0.1970	0.7295
36 93	9	at t = 0.45 T	0.6477	0.2818	0.0705	-	-	0.1057	0.7108	0.1520	0.0315	-	0.0352	0.1131	0.7145	0.1057	0.0315	0.0126	0.0505	0.1761	0.7219	0.0389	-	0.0126	0.0541	0.1835	0.7497
44 93	10	at t = 0.50 T	0.6797	0.2562	0.0641	-	-	0.0961	0.7348	0.1416	0.0275	-	0.0320	0.1051	0.7393	0.0961	0.0275	0.0110	0.0441	0.1601	0.7483	0.0365	-	0.0110	0.0485	0.1691	0.7713
52.93	11	at t = 0.55 T	0.7117	0.2306	0.0577	-	-	0.0865	0.7588	0.1312	0.0235	-	0.0288	0.0971	0.7641	0.0865	0.0235	0.0094	0.0377	0.1441	0.7747	0.0341	-	0.0094	0.0429	0.1547	0.7929
60.93	12	at t = 0.60 T	0.7437	0.2050	0.0513	-	-	0.0769	0.7828	0.1208	0.0195	-	0.0256	0.0891	0.7889	0.0769	0.0195	0.0078	0.0313	0.1281	0.8011	0.0317	-	0.0078	0.0373	0.1403	0.8145
68.50	13	at t = 0.65 T	0.7740	0.1808	0.0452	-	-	0.0678	0.8055	0.1110	0.0158	-	0.0226	0.0815	0.8124	0.0678	0.0158	0.0063	0.0252	0.1130	0.8261	0.0295	-	0.0063	0.0321	0.1267	0.8350
76.00	14	at t = 0.70 T	0.8040	0.1568	0.0392	-	-	0.0588	0.8280	0.1012	0.0120	-	0.0196	0.0740	0.8356	0.0588	0.0120	0.0048	0.0192	0.0980	0.8508	0.0272	-	0.0048	0.0268	0.1132	0.8552
83.00	15	at t = 0.75 T	0.8320	0.1344	0.0336	-	-	0.0504	0.8490	0.0921	0.0085	-	0.0168	0.0670	0.8573	0.0504	0.0085	0.0034	0.0136	0.0840	0.8739	0.0251	-	0.0034	0.0219	0.1006	0.8741
89.50	16	at t = 0.80 T	0.8580	0.1136	0.0284	-	-	0.0426	0.8685	0.0837	0.0053	-	0.0142	0.0605	0.8775	0.0426	0.0053	0.0021	0.0084	0.0710	0.8954	0.0232	-	0.0021	0.0174	0.0889	0.8917
93.50	17	at t = 0.85 T	0.8740	0.1008	0.0252	-	-	0.0378	0.8805	0.0785	0.0033	-	0.0126	0.0565	0.8899	0.0378	0.0033	0.0013	0.0052	0.0630	0.9086	0.0220	-	0.0013	0.0146	0.0817	0.9025
96.00	18	at t = 0.90 T	0.8840	0.0928	0.0232	-	-	0.0348	0.8880	0.0752	0.0020	-	0.0116	0.0540	0.8976	0.0348	0.0020	0.0008	0.0032	0.0580	0.9168	0.0212	-	0.0008	0.0128	0.0772	0.9092
98.50	19	at t = 0.95 T	0.8940	0.0848	0.0212	-	-	0.0318	0.8955	0.0720	0.0007	-	0.0106	0.0515	0.9054	0.0318	0.0007	0.0003	0.0012	0.0530	0.9251	0.0205	-	0.0003	0.0111	0.0727	0.9160
100 00	20	at t = 1.00 T	**0.9000**	**0.0800**	**0.0200**	-	-	**0.0300**	**0.9000**	**0.0700**	-	-	**0.0100**	**0.0500**	**0.9100**	**0.0300**	-	-	-	**0.0500**	**0.9300**	**0.0200**	-	-	**0.0100**	**0.0700**	**0.9200**


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Quality Forecasting Model

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.5000**	**0.4000**	**0.1000**	-	-	0.5200	0.3840	0.0960	-	-	0.5340	0.3728	0.0932	-	-	0.5500	0.3600	0.0900	-	-
B						**0.1500**	**0.6000**	**0.2000**	**0.0500**	-	0.1440	0.6150	0.1935	0.0475	-	0.1398	0.6255	0.1890	0.0458	-	0.1350	0.6375	0.1838	0.0438	-
C						**0.0500**	**0.1500**	**0.6000**	**0.1500**	**0.0500**	0.0480	0.1450	0.6155	0.1440	0.0475	0.0466	0.1415	0.6264	0.1398	0.0458	0.0450	0.1375	0.6388	0.1350	0.0438
D						**0.0200**	**0.0800**	**0.2500**	**0.6000**	**0.0500**	0.0190	0.0760	0.2400	0.6165	0.0485	0.0183	0.0732	0.2330	0.6281	0.0475	0.0175	0.0700	0.2250	0.6413	0.0463
F						-	**0.0200**	**0.0800**	**0.2500**	**0.6500**	-	0.0190	0.0765	0.2410	0.6635	-	0.0183	0.0741	0.2347	0.6730	-	0.0175	0.0713	0.2275	0.6838

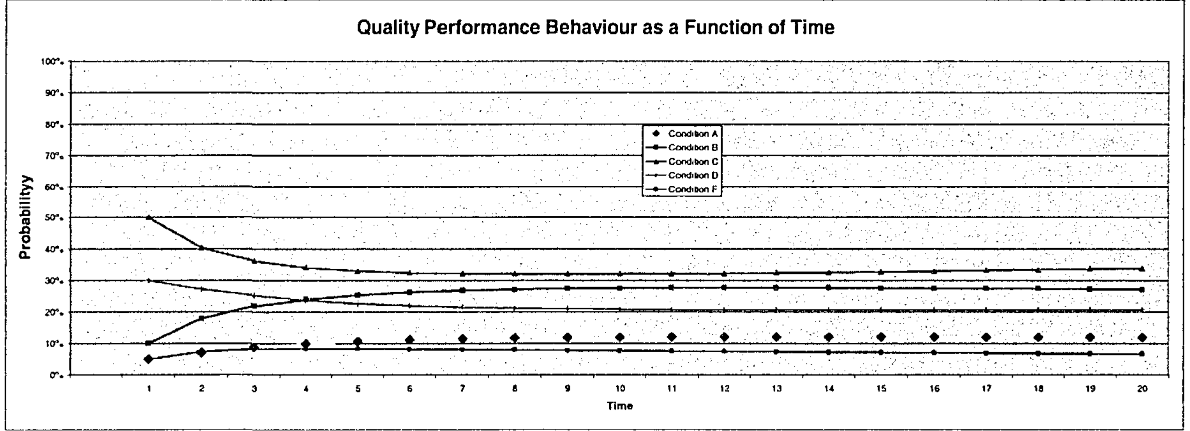
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5680	0.3456	0.0864	-	-	0.5897	0.3282	0.0821	-	-	0.6177	0.3058	0.0765	-	-	0.6477	0.2818	0.0705	-	-	0.6797	0.2562	0.0641	-	-
B	0.1296	0.6510	0.1779	0.0415	-	0.1231	0.6673	0.1708	0.0388	-	0.1147	0.6883	0.1617	0.0353	-	0.1057	0.7108	0.1520	0.0315	-	0.0961	0.7348	0.1416	0.0275	-
C	0.0432	0.1330	0.6527	0.1296	0.0415	0.0410	0.1276	0.6695	0.1231	0.0388	0.0382	0.1206	0.6912	0.1147	0.0353	0.0352	0.1131	0.7145	0.1057	0.0315	0.0320	0.1051	0.7393	0.0961	0.0275
D	0.0166	0.0664	0.2160	0.6561	0.0449	0.0155	0.0621	0.2051	0.6740	0.0433	0.0141	0.0565	0.1911	0.6971	0.0412	0.0126	0.0505	0.1761	0.7219	0.0389	0.0110	0.0441	0.1601	0.7483	0.0365
F	-	0.0166	0.0681	0.2194	0.6959	-	0.0155	0.0643	0.2096	0.7106	-	0.0141	0.0594	0.1970	0.7295	-	0.0126	0.0541	0.1835	0.7497	-	0.0110	0.0485	0.1691	0.7713

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7117	0.2306	0.0577	-	-	0.7437	0.2050	0.0513	-	-	0.7740	0.1808	0.0452	-	-	0.8040	0.1568	0.0392	-	-	0.8320	0.1344	0.0336	-	-
B	0.0865	0.7588	0.1312	0.0235	-	0.0769	0.7828	0.1208	0.0195	-	0.0678	0.8055	0.1110	0.0158	-	0.0588	0.8280	0.1012	0.0120	-	0.0504	0.8490	0.0921	0.0085	-
C	0.0288	0.0971	0.7641	0.0865	0.0235	0.0256	0.0891	0.7889	0.0769	0.0195	0.0226	0.0815	0.8124	0.0678	0.0158	0.0196	0.0740	0.8356	0.0588	0.0120	0.0168	0.0670	0.8573	0.0504	0.0085
D	0.0094	0.0377	0.1441	0.7747	0.0341	0.0078	0.0313	0.1281	0.8011	0.0317	0.0063	0.0252	0.1130	0.8261	0.0295	0.0048	0.0192	0.0980	0.8508	0.0272	0.0034	0.0136	0.0840	0.8739	0.0251
F	-	0.0094	0.0429	0.1547	0.7929	-	0.0078	0.0373	0.1403	0.8145	-	0.0063	0.0321	0.1267	0.8350	-	0.0048	0.0268	0.1132	0.8552	-	0.0034	0.0219	0.1006	0.8741

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8580	0.1136	0.0284	-	-	0.8740	0.1008	0.0252	-	-	0.8840	0.0928	0.0232	-	-	0.8940	0.0848	0.0212	-	-	**0.9000**	**0.0800**	**0.0200**	-	-
B	0.0426	0.8685	0.0837	0.0053	-	0.0378	0.8805	0.0785	0.0033	-	0.0348	0.8880	0.0752	0.0020	-	0.0318	0.8955	0.0720	0.0007	-	**0.0300**	**0.9000**	**0.0700**	-	-
C	0.0142	0.0605	0.8775	0.0426	0.0053	0.0126	0.0565	0.8899	0.0378	0.0033	0.0116	0.0540	0.8976	0.0348	0.0020	0.0106	0.0515	0.9054	0.0318	0.0007	**0.0100**	**0.0500**	**0.9100**	**0.0300**	-
D	0.0021	0.0084	0.0710	0.8954	0.0232	0.0013	0.0052	0.0630	0.9086	0.0220	0.0008	0.0032	0.0580	0.9168	0.0212	0.0003	0.0012	0.0530	0.9251	0.0205	-	-	**0.0500**	**0.9300**	**0.0200**
F	-	0.0021	0.0174	0.0889	0.8917	-	0.0013	0.0146	0.0817	0.9025	-	0.0008	0.0128	0.0772	0.9092	-	0.0003	0.0111	0.0727	0.9160	-	-	**0.0100**	**0.0700**	**0.9200**

Initial Probability Vector obtained from company historic records

Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Quality Index	Expected Value	The expected quality performance at the end of the project given the latest actual status is equal to :
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80	at t = 0.85	at t = 0.90	at t = 0.95	at t = 1.00 T			
CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Pro	State Pro	State Pro	State Pro	State Proba	QPI	QPI	
A		5%	7.10%	8.74%	9.87%	10.62%	11.12%	11.46%	11.69%	11.84%	11.93%	12.00%	12.03%	12.04%	12.04%	12.03%	12.00%	11.97%	11.93%	11.90%	11.86%	1.20	0.14	
B		10%	18.00%	21.86%	24.04%	25.37%	26.22%	26.78%	27.15%	27.39%	27.53%	27.61%	27.64%	27.64%	27.60%	27.54%	27.45%	27.36%	27.27%	27.18%	27.09%	1.10	0.30	
C		50%	40.40%	36.13%	34.05%	32.99%	32.45%	32.17%	32.05%	32.02%	32.05%	32.12%	32.23%	32.37%	32.54%	32.73%	32.95%	33.18%	33.40%	33.63%	33.84%	1.00	0.34	
D		30%	27.25%	25.22%	23.78%	22.78%	22.08%	21.60%	21.26%	21.03%	20.88%	20.77%	20.70%	20.66%	20.63%	20.63%	20.64%	20.65%	20.67%	20.70%	20.72%	0.90	0.19	**101.71%**
F		5%	7.25%	8.05%	8.27%	8.24%	8.13%	7.99%	7.85%	7.72%	7.61%	7.50%	7.39%	7.29%	7.19%	7.08%	6.96%	6.84%	6.72%	6.61%	6.49%	0.80	0.05	or Within TARGET
sum		**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	Total	1.017	
		0.98	0.99	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02			



APPENDIX (J)

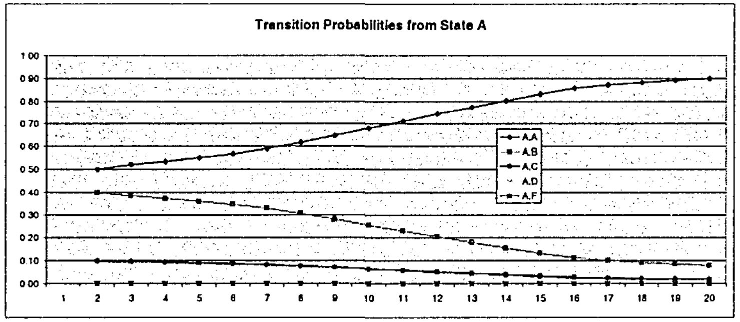
Forecasting Project Performance using Dynamic Markov Chains

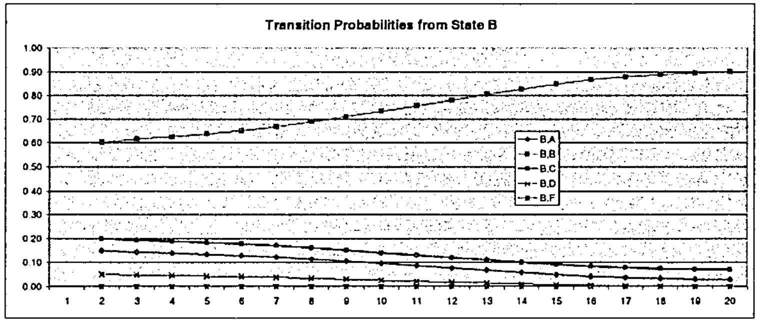
Quality Forecasting Update

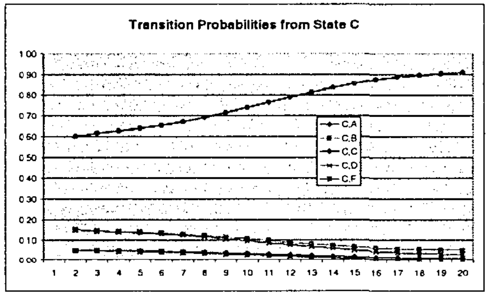
Transition Probabilities as a Function of Project Duration (T)

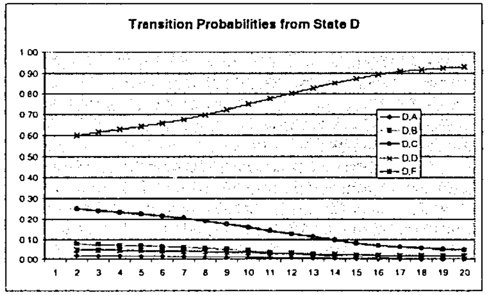
boundary conditions derived based on company historic database

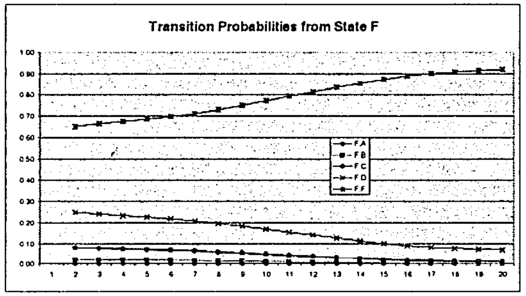
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	**0.5000**	**0.4000**	**0.1000**	-	-	**0.1500**	**0.6000**	**0.2000**	**0.0500**	-	**0.0500**	**0.1500**	**0.6000**	**0.1500**	**0.0500**	**0.0200**	**0.0800**	**0.2500**	**0.6000**	**0.0500**	-	**0.0200**	**0.0800**	**0.2500**	**0.6500**
5.00	3	at t = 0.15 T	0.5200	0.3840	0.0960	-	-	0.1440	0.6150	0.1935	0.0475	-	0.0480	0.1450	0.6155	0.1440	0.0475	0.0190	0.0760	0.2400	0.6165	0.0485	-	0.0190	0.0765	0.2410	0.6635
8.50	4	at t = 0.20 T	0.5340	0.3728	0.0932	-	-	0.1398	0.6255	0.1890	0.0458	-	0.0466	0.1415	0.6264	0.1398	0.0458	0.0183	0.0732	0.2330	0.6281	0.0475	-	0.0183	0.0741	0.2347	0.6730
12.50	5	at t = 0.25 T	0.5500	0.3600	0.0900	-	-	0.1350	0.6375	0.1838	0.0438	-	0.0450	0.1375	0.6388	0.1350	0.0438	0.0175	0.0700	0.2250	0.6413	0.0463	-	0.0175	0.0713	0.2275	0.6838
17.00	6	at t = 0.30 T	0.5680	0.3456	0.0864	-	-	0.1296	0.6510	0.1779	0.0415	-	0.0432	0.1330	0.6527	0.1296	0.0415	0.0166	0.0664	0.2160	0.6561	0.0449	-	0.0166	0.0681	0.2194	0.6959
22.43	7	at t = 0.35 T	0.5897	0.3282	0.0821	-	-	0.1231	0.6673	0.1708	0.0388	-	0.0410	0.1276	0.6695	0.1231	0.0388	0.0155	0.0621	0.2051	0.6740	0.0433	-	0.0155	0.0643	0.2096	0.7106
29.43	8	at t = 0.40 T	0.6177	0.3058	0.0765	-	-	0.1147	0.6883	0.1617	0.0353	-	0.0382	0.1206	0.6912	0.1147	0.0353	0.0141	0.0565	0.1911	0.6971	0.0412	-	0.0141	0.0594	0.1970	0.7295
36.93	9	at t = 0.45 T	0.6477	0.2818	0.0705	-	-	0.1057	0.7108	0.1520	0.0315	-	0.0352	0.1131	0.7145	0.1057	0.0315	0.0126	0.0505	0.1761	0.7219	0.0389	-	0.0126	0.0541	0.1835	0.7497
44.93	10	at t = 0.50 T	0.6797	0.2562	0.0641	-	-	0.0961	0.7348	0.1416	0.0275	-	0.0320	0.1051	0.7393	0.0961	0.0275	0.0110	0.0441	0.1601	0.7483	0.0365	-	0.0110	0.0485	0.1691	0.7713
52.93	11	at t = 0.55 T	0.7117	0.2306	0.0577	-	-	0.0865	0.7588	0.1312	0.0235	-	0.0288	0.0971	0.7641	0.0865	0.0235	0.0094	0.0377	0.1441	0.7747	0.0341	-	0.0094	0.0429	0.1547	0.7929
60.93	12	at t = 0.60 T	0.7437	0.2050	0.0513	-	-	0.0769	0.7828	0.1208	0.0195	-	0.0256	0.0891	0.7889	0.0769	0.0195	0.0078	0.0313	0.1281	0.8011	0.0317	-	0.0078	0.0373	0.1403	0.8145
68.50	13	at t = 0.65 T	0.7740	0.1808	0.0452	-	-	0.0678	0.8055	0.1110	0.0158	-	0.0226	0.0815	0.8124	0.0678	0.0158	0.0063	0.0252	0.1130	0.8261	0.0295	-	0.0063	0.0321	0.1267	0.8350
76.00	14	at t = 0.70 T	0.8040	0.1568	0.0392	-	-	0.0588	0.8280	0.1012	0.0120	-	0.0196	0.0740	0.8356	0.0588	0.0120	0.0048	0.0192	0.0980	0.8508	0.0272	-	0.0048	0.0268	0.1132	0.8552
83.00	15	at t = 0.75 T	0.8320	0.1344	0.0336	-	-	0.0504	0.8490	0.0921	0.0085	-	0.0168	0.0670	0.8573	0.0504	0.0085	0.0034	0.0136	0.0840	0.8739	0.0251	-	0.0034	0.0219	0.1006	0.8741
89.50	16	at t = 0.80 T	0.8580	0.1136	0.0284	-	-	0.0426	0.8685	0.0837	0.0053	-	0.0142	0.0605	0.8775	0.0426	0.0053	0.0021	0.0084	0.0710	0.8954	0.0232	-	0.0021	0.0174	0.0889	0.8917
93.50	17	at t = 0.85 T	0.8740	0.1008	0.0252	-	-	0.0378	0.8805	0.0785	0.0033	-	0.0126	0.0565	0.8899	0.0378	0.0033	0.0013	0.0052	0.0630	0.9086	0.0220	-	0.0013	0.0146	0.0817	0.9025
96.00	18	at t = 0.90 T	0.8840	0.0928	0.0232	-	-	0.0348	0.8880	0.0752	0.0020	-	0.0116	0.0540	0.8976	0.0348	0.0020	0.0008	0.0032	0.0580	0.9168	0.0212	-	0.0008	0.0128	0.0772	0.9092
98.50	19	at t = 0.95 T	0.8940	0.0848	0.0212	-	-	0.0318	0.8955	0.0720	0.0007	-	0.0106	0.0515	0.9054	0.0318	0.0007	0.0003	0.0012	0.0530	0.9251	0.0205	-	0.0003	0.0111	0.0727	0.9160
100.00	20	at t = 1.00 T	**0.9000**	**0.0800**	**0.0200**	-	-	**0.0300**	**0.9000**	**0.0700**	-	-	**0.0100**	**0.0500**	**0.9100**	**0.0300**	-	-	-	**0.0500**	**0.9300**	**0.0200**	-	-	**0.0100**	**0.0700**	**0.9200**


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

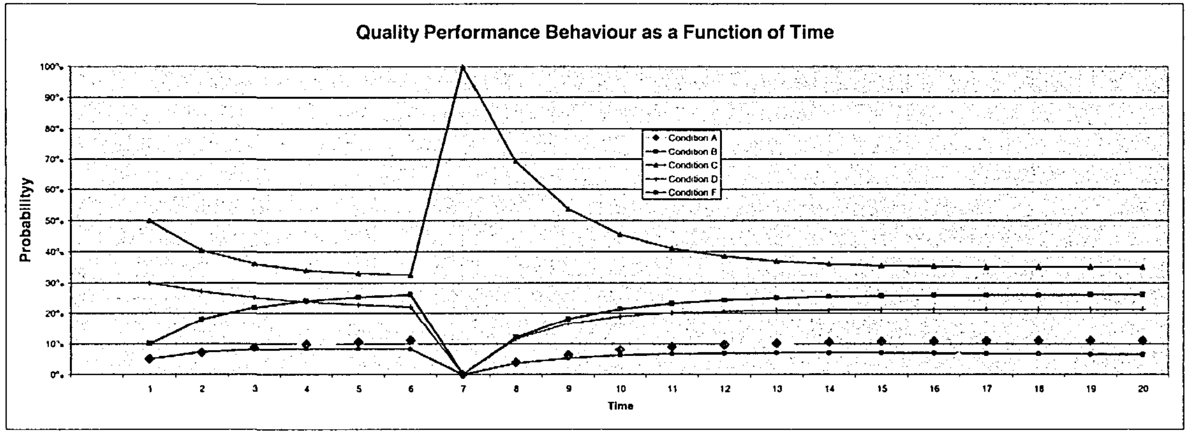
Forecasting Project Performance using Dynamic Markov Chains

Quality Forecasting Update

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						0.5000	0.4000	0.1000	-	-	0.5200	0.3840	0.0960	-	-	0.5340	0.3728	0.0932	-	-	0.5500	0.3600	0.0900	-	-
B						0.1500	0.6000	0.2000	0.0500	-	0.1440	0.6150	0.1935	0.0475	-	0.1398	0.6255	0.1890	0.0458	-	0.1350	0.6375	0.1838	0.0438	-
C						0.0500	0.1500	0.6000	0.1500	0.0500	0.0480	0.1450	0.6155	0.1440	0.0475	0.0466	0.1415	0.6264	0.1398	0.0458	0.0450	0.1375	0.6388	0.1350	0.0438
D						0.0200	0.0800	0.2500	0.6000	0.0500	0.0190	0.0760	0.2400	0.6165	0.0485	0.0183	0.0732	0.2330	0.6281	0.0475	0.0175	0.0700	0.2250	0.6413	0.0463
F						-	0.0200	0.0800	0.2500	0.6500	-	0.0190	0.0765	0.2410	0.6635	-	0.0183	0.0741	0.2347	0.6730	-	0.0175	0.0713	0.2275	0.6838
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.5680	0.3456	0.0864	-	-	0.5897	0.3282	0.0821	-	-	0.6177	0.3058	0.0765	-	-	0.6477	0.2818	0.0705	-	-	0.6797	0.2562	0.0641	-	-
B	0.1296	0.6510	0.1779	0.0415	-	0.1231	0.6673	0.1708	0.0388	-	0.1147	0.6883	0.1617	0.0353	-	0.1057	0.7108	0.1520	0.0315	-	0.0961	0.7348	0.1416	0.0275	-
C	0.0432	0.1330	0.6527	0.1296	0.0415	0.0410	0.1276	0.6695	0.1231	0.0388	0.0382	0.1206	0.6912	0.1147	0.0353	0.0352	0.1131	0.7145	0.1057	0.0315	0.0320	0.1051	0.7393	0.0961	0.0275
D	0.0166	0.0664	0.2160	0.6561	0.0449	0.0155	0.0621	0.2051	0.6740	0.0433	0.0141	0.0565	0.1911	0.6971	0.0412	0.0126	0.0505	0.1761	0.7219	0.0389	0.0110	0.0441	0.1601	0.7483	0.0365
F	-	0.0166	0.0681	0.2194	0.6959	-	0.0155	0.0643	0.2096	0.7106	-	0.0141	0.0594	0.1970	0.7295	-	0.0126	0.0541	0.1835	0.7497	-	0.0110	0.0485	0.1691	0.7713
	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7117	0.2306	0.0577	-	-	0.7437	0.2050	0.0513	-	-	0.7740	0.1808	0.0452	-	-	0.8040	0.1568	0.0392	-	-	0.8320	0.1344	0.0336	-	-
B	0.0865	0.7588	0.1312	0.0235	-	0.0769	0.7828	0.1208	0.0195	-	0.0678	0.8055	0.1110	0.0158	-	0.0588	0.8280	0.1012	0.0120	-	0.0504	0.8490	0.0921	0.0085	-
C	0.0288	0.0971	0.7641	0.0865	0.0235	0.0256	0.0891	0.7889	0.0769	0.0195	0.0226	0.0815	0.8124	0.0678	0.0158	0.0196	0.0740	0.8356	0.0588	0.0120	0.0168	0.0670	0.8573	0.0504	0.0085
D	0.0094	0.0377	0.1441	0.7747	0.0341	0.0078	0.0313	0.1281	0.8011	0.0317	0.0063	0.0252	0.1130	0.8261	0.0295	0.0048	0.0192	0.0980	0.8508	0.0272	0.0034	0.0136	0.0840	0.8739	0.0251
F	-	0.0094	0.0429	0.1547	0.7929	-	0.0078	0.0373	0.1403	0.8145	-	0.0063	0.0321	0.1267	0.8350	-	0.0048	0.0268	0.1132	0.8552	-	0.0034	0.0219	0.1006	0.8741
	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8580	0.1136	0.0284	-	-	0.8740	0.1008	0.0252	-	-	0.8840	0.0928	0.0232	-	-	0.8940	0.0848	0.0212	-	-	0.9000	0.0800	0.0200	-	-
B	0.0426	0.8685	0.0837	0.0053	-	0.0378	0.8805	0.0785	0.0033	-	0.0348	0.8880	0.0752	0.0020	-	0.0318	0.8955	0.0720	0.0007	-	0.0300	0.9000	0.0700	-	-
C	0.0142	0.0605	0.8775	0.0426	0.0053	0.0126	0.0565	0.8899	0.0378	0.0033	0.0116	0.0540	0.8976	0.0348	0.0020	0.0106	0.0515	0.9054	0.0318	0.0007	0.0100	0.0500	0.9100	0.0300	-
D	0.0021	0.0084	0.0710	0.8954	0.0232	0.0013	0.0052	0.0630	0.9086	0.0220	0.0008	0.0032	0.0580	0.9168	0.0212	0.0003	0.0012	0.0530	0.9251	0.0205	-	-	0.0500	0.9300	0.0200
F	-	0.0021	0.0174	0.0889	0.8917	-	0.0013	0.0146	0.0817	0.9025	-	0.0008	0.0128	0.0772	0.9092	-	0.0003	0.0111	0.0727	0.9160	-	-	0.0100	0.0700	0.9200

Initial Probability Vector obtained from company historic records

Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Quality Index	Expected Value	The expected quality performance at the end of the project given the latest actual status is equal to :
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80	at t = 0.85	at t = 0.90	at t = 0.95	at t = 1.00 T			
CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probat	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	QPI	QPI	
A		5%	7.10%	8.74%	9.87%	10.62%	11.12%	0.00%	3.82%	6.33%	7.94%	8.99%	9.68%	10.15%	10.46%	10.66%	10.80%	10.89%	10.96%	11.01%	11.04%	1.20	0.13	
B		10%	18.00%	21.86%	24.04%	25.37%	26.22%	0.00%	12.06%	18.09%	21.34%	23.22%	24.36%	25.08%	25.52%	25.80%	25.96%	26.06%	26.12%	26.15%	26.17%	1.10	0.29	
C		50%	40.40%	36.13%	34.05%	32.99%	32.45%	100.00%	69.12%	53.70%	45.58%	41.09%	38.50%	36.97%	36.06%	35.53%	35.26%	35.12%	35.05%	35.04%	35.07%	1.00	0.35	
D		30%	27.25%	25.22%	23.78%	22.78%	22.08%	0.00%	11.47%	16.61%	18.98%	20.10%	20.64%	20.91%	21.04%	21.12%	21.17%	21.21%	21.24%	21.26%	21.28%	0.90	0.19	101.41%
F		5%	7.25%	8.05%	8.27%	8.24%	8.13%	0.00%	3.53%	5.27%	6.15%	6.60%	6.81%	6.90%	6.92%	6.88%	6.81%	6.73%	6.63%	6.54%	6.44%	0.80	0.05	or Within TARGET
sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	1.014	
		0.98	0.99	1.00	1.00	1.01	1.01	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01			



Quality Performance Behaviour as a Function of Time

APPENDIX (J)

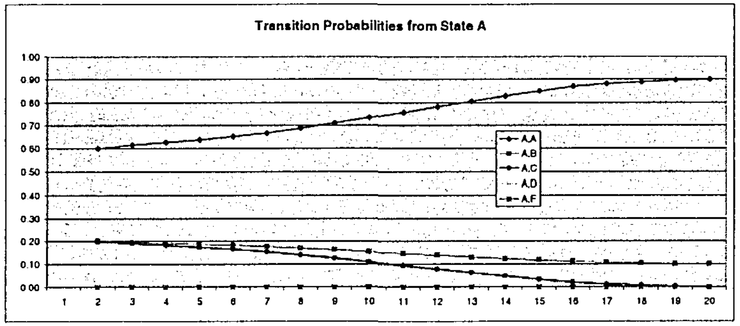
Forecasting Project Performance using Dynamic Markov Chains

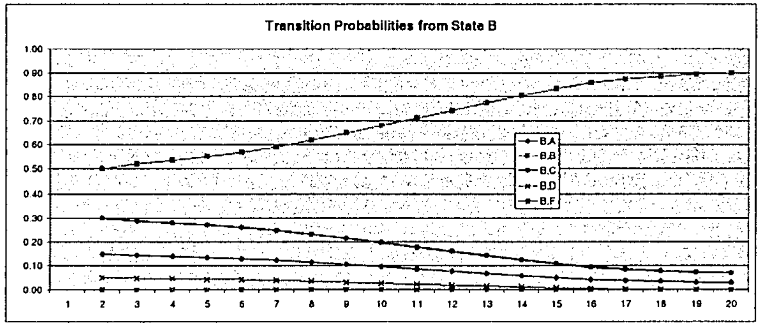
Team Satisfaction Forecasting Model

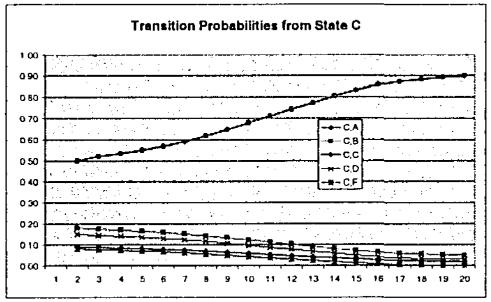
Transition Probabilities as a Function of Project Duration (T)

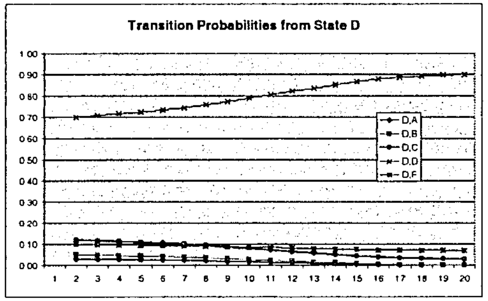
boundary conditions derived based on company historic database

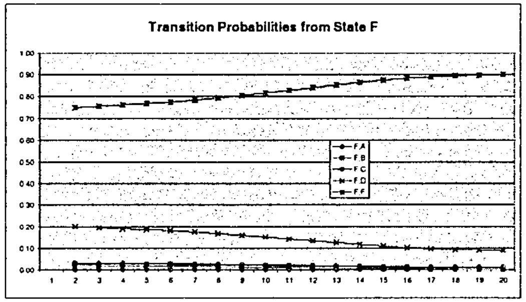
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	0.6000	0.2000	0.2000	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1800	0.5000	0.1500	0.0800	0.0300	0.0500	0.1200	0.7000	0.1000	-	0.0200	0.0300	0.2000	0.7500
5.00	3	at t = 0.15 T	0.6150	0.1950	0.1900	-	-	0.1440	0.5200	0.2885	0.0475	-	0.0865	0.1735	0.5200	0.1440	0.0760	0.0285	0.0475	0.1155	0.7100	0.0985	-	0.0190	0.0290	0.1945	0.7575
8.50	4	at t = 0.20 T	0.6255	0.1915	0.1830	-	-	0.1398	0.5340	0.2805	0.0458	-	0.0841	0.1690	0.5340	0.1398	0.0732	0.0275	0.0458	0.1124	0.7170	0.0975	-	0.0183	0.0283	0.1907	0.7628
12.50	5	at t = 0.25 T	0.6375	0.1875	0.1750	-	-	0.1350	0.5500	0.2713	0.0438	-	0.0813	0.1638	0.5500	0.1350	0.0700	0.0263	0.0438	0.1088	0.7250	0.0963	-	0.0175	0.0275	0.1863	0.7688
17.00	6	at t = 0.30 T	0.6510	0.1830	0.1660	-	-	0.1296	0.5680	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664	0.0249	0.0415	0.1047	0.7340	0.0949	-	0.0166	0.0266	0.1813	0.7755
22.43	7	at t = 0.35 T	0.6673	0.1776	0.1551	-	-	0.1231	0.5897	0.2484	0.0388	-	0.0743	0.1508	0.5897	0.1231	0.0621	0.0233	0.0388	0.0998	0.7449	0.0933	-	0.0155	0.0255	0.1753	0.7836
29.43	8	at t = 0.40 T	0.6883	0.1706	0.1411	-	-	0.1147	0.6177	0.2323	0.0353	-	0.0694	0.1417	0.6177	0.1147	0.0565	0.0212	0.0353	0.0935	0.7589	0.0912	-	0.0141	0.0241	0.1676	0.7941
36.93	9	at t = 0.45 T	0.7108	0.1631	0.1261	-	-	0.1057	0.6477	0.2151	0.0315	-	0.0641	0.1320	0.6477	0.1057	0.0505	0.0189	0.0315	0.0868	0.7739	0.0889	-	0.0126	0.0226	0.1594	0.8054
44.93	10	at t = 0.50 T	0.7348	0.1551	0.1101	-	-	0.0961	0.6797	0.1967	0.0275	-	0.0585	0.1216	0.6797	0.0961	0.0441	0.0165	0.0275	0.0796	0.7899	0.0865	-	0.0110	0.0210	0.1506	0.8174
52.93	11	at t = 0.55 T	0.7588	0.1471	0.0941	-	-	0.0865	0.7117	0.1783	0.0235	-	0.0529	0.1112	0.7117	0.0865	0.0377	0.0141	0.0235	0.0724	0.8059	0.0841	-	0.0094	0.0194	0.1418	0.8294
60.93	12	at t = 0.60 T	0.7828	0.1391	0.0781	-	-	0.0769	0.7437	0.1599	0.0195	-	0.0473	0.1008	0.7437	0.0769	0.0313	0.0117	0.0195	0.0652	0.8219	0.0817	-	0.0078	0.0178	0.1330	0.8414
68.50	13	at t = 0.65 T	0.8055	0.1315	0.0630	-	-	0.0678	0.7740	0.1425	0.0158	-	0.0421	0.0910	0.7740	0.0678	0.0252	0.0095	0.0158	0.0584	0.8370	0.0795	-	0.0063	0.0163	0.1247	0.8528
76.00	14	at t = 0.70 T	0.8280	0.1240	0.0480	-	-	0.0588	0.8040	0.1252	0.0120	-	0.0368	0.0812	0.8040	0.0588	0.0192	0.0072	0.0120	0.0516	0.8520	0.0772	-	0.0048	0.0148	0.1164	0.8640
83.00	15	at t = 0.75 T	0.8490	0.1170	0.0340	-	-	0.0504	0.8320	0.1091	0.0085	-	0.0319	0.0721	0.8320	0.0504	0.0136	0.0051	0.0085	0.0453	0.8660	0.0751	-	0.0034	0.0134	0.1087	0.8745
89.50	16	at t = 0.80 T	0.8685	0.1105	0.0210	-	-	0.0426	0.8580	0.0942	0.0053	-	0.0274	0.0637	0.8580	0.0426	0.0084	0.0032	0.0053	0.0395	0.8790	0.0732	-	0.0021	0.0121	0.1016	0.8843
93.50	17	at t = 0.85 T	0.8805	0.1065	0.0130	-	-	0.0378	0.8740	0.0850	0.0033	-	0.0246	0.0585	0.8740	0.0378	0.0052	0.0020	0.0033	0.0359	0.8870	0.0720	-	0.0013	0.0113	0.0972	0.8903
96.00	18	at t = 0.90 T	0.8880	0.1040	0.0080	-	-	0.0348	0.8840	0.0792	0.0020	-	0.0228	0.0552	0.8840	0.0348	0.0032	0.0012	0.0020	0.0336	0.8920	0.0712	-	0.0008	0.0108	0.0944	0.8940
98.50	19	at t = 0.95 T	0.8955	0.1015	0.0030	-	-	0.0318	0.8940	0.0735	0.0007	-	0.0211	0.0520	0.8940	0.0318	0.0012	0.0004	0.0007	0.0314	0.8970	0.0705	-	0.0003	0.0103	0.0917	0.8978
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0300	0.9000	0.0700	-	-	0.0100	0.0900	0.9000


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Team Satisfaction Forecasting Model

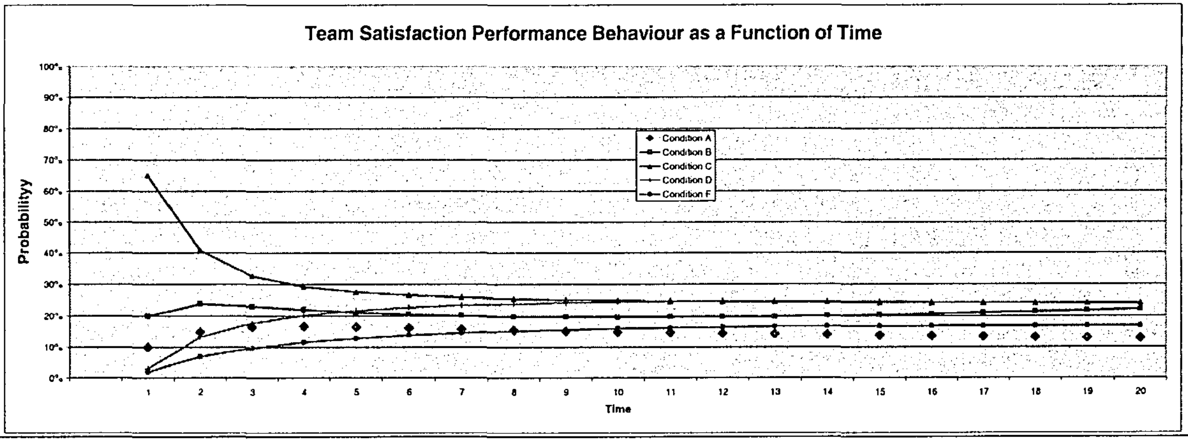
	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						0.6000	0.2000	0.2000	-	-	0.6150	0.1950	0.1900	-	-	0.6255	0.1915	0.1830	-	-	0.6375	0.1875	0.1750	-	-
B						0.1500	0.5000	0.3000	0.0500	-	0.1440	0.5200	0.2885	0.0475	-	0.1398	0.5340	0.2805	0.0458	-	0.1350	0.5500	0.2713	0.0438	-
C						0.0900	0.1800	0.5000	0.1500	0.0800	0.0865	0.1735	0.5200	0.1440	0.0760	0.0841	0.1690	0.5340	0.1398	0.0732	0.0813	0.1638	0.5500	0.1350	0.0700
D						0.0300	0.0500	0.1200	0.7000	0.1000	0.0285	0.0475	0.1155	0.7100	0.0985	0.0275	0.0458	0.1124	0.7170	0.0975	0.0263	0.0438	0.1088	0.7250	0.0963
F						-	0.0200	0.0300	0.2000	0.7500	-	0.0190	0.0290	0.1945	0.7575	-	0.0183	0.0283	0.1907	0.7628	-	0.0175	0.0275	0.1863	0.7688

	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6510	0.1830	0.1660	-	-	0.6673	0.1776	0.1551	-	-	0.6883	0.1706	0.1411	-	-	0.7108	0.1631	0.1261	-	-	0.7348	0.1551	0.1101	-	-
B	0.1296	0.5680	0.2609	0.0415	-	0.1231	0.5897	0.2484	0.0388	-	0.1147	0.6177	0.2323	0.0353	-	0.1057	0.6477	0.2151	0.0315	-	0.0961	0.6797	0.1967	0.0275	-
C	0.0781	0.1579	0.5680	0.1296	0.0664	0.0743	0.1508	0.5897	0.1231	0.0621	0.0694	0.1417	0.6177	0.1147	0.0565	0.0641	0.1320	0.6477	0.1057	0.0505	0.0585	0.1216	0.6797	0.0961	0.0441
D	0.0249	0.0415	0.1047	0.7340	0.0949	0.0233	0.0388	0.0998	0.7449	0.0933	0.0212	0.0353	0.0935	0.7589	0.0912	0.0189	0.0315	0.0868	0.7739	0.0889	0.0165	0.0275	0.0796	0.7899	0.0865
F	-	0.0166	0.0266	0.1813	0.7755	-	0.0155	0.0255	0.1753	0.7836	-	0.0141	0.0241	0.1676	0.7941	-	0.0126	0.0226	0.1594	0.8054	-	0.0110	0.0210	0.1506	0.8174

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7588	0.1471	0.0941	-	-	0.7828	0.1391	0.0781	-	-	0.8055	0.1315	0.0630	-	-	0.8280	0.1240	0.0480	-	-	0.8490	0.1170	0.0340	-	-
B	0.0865	0.7117	0.1783	0.0235	-	0.0769	0.7437	0.1599	0.0195	-	0.0678	0.7740	0.1425	0.0158	-	0.0588	0.8040	0.1252	0.0120	-	0.0504	0.8320	0.1091	0.0085	-
C	0.0529	0.1112	0.7117	0.0865	0.0377	0.0473	0.1008	0.7437	0.0769	0.0313	0.0421	0.0910	0.7740	0.0678	0.0252	0.0368	0.0812	0.8040	0.0588	0.0192	0.0319	0.0721	0.8320	0.0504	0.0136
D	0.0141	0.0235	0.0724	0.8059	0.0841	0.0117	0.0195	0.0652	0.8219	0.0817	0.0095	0.0158	0.0584	0.8370	0.0795	0.0072	0.0120	0.0516	0.8520	0.0772	0.0051	0.0085	0.0453	0.8660	0.0751
F	-	0.0094	0.0194	0.1418	0.8294	-	0.0078	0.0178	0.1330	0.8414	-	0.0063	0.0163	0.1247	0.8528	-	0.0048	0.0148	0.1164	0.8640	-	0.0034	0.0134	0.1087	0.8745

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8685	0.1105	0.0210	-	-	0.8805	0.1065	0.0130	-	-	0.8880	0.1040	0.0080	-	-	0.8955	0.1015	0.0030	-	-	0.9000	0.1000	-	-	-
B	0.0426	0.8580	0.0942	0.0053	-	0.0378	0.8740	0.0850	0.0033	-	0.0348	0.8840	0.0792	0.0020	-	0.0318	0.8940	0.0735	0.0007	-	0.0300	0.9000	0.0700	-	-
C	0.0274	0.0637	0.8580	0.0426	0.0084	0.0246	0.0585	0.8740	0.0378	0.0052	0.0228	0.0552	0.8840	0.0348	0.0032	0.0211	0.0520	0.8940	0.0318	0.0012	0.0200	0.0500	0.9000	0.0300	-
D	0.0032	0.0053	0.0395	0.8790	0.0732	0.0020	0.0033	0.0359	0.8870	0.0720	0.0012	0.0020	0.0336	0.8920	0.0712	0.0004	0.0007	0.0314	0.8970	0.0705	-	-	0.0300	0.9000	0.0700
F	-	0.0021	0.0121	0.1016	0.8843	-	0.0013	0.0113	0.0972	0.8903	-	0.0008	0.0108	0.0944	0.8940	-	0.0003	0.0103	0.0917	0.8978	-	-	0.0100	0.0900	0.9000

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Team Satisf Index	Expected Value	
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00 T			The expected team satisfaction performance at the end of the project given the latest actual status is equal to :
	CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probal	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	TSI	TSI	
	A		10%	14.94%	16.55%	16.83%	16.62%	16.26%	15.88%	15.53%	15.22%	14.95%	14.71%	14.48%	14.27%	14.07%	13.86%	13.65%	13.45%	13.26%	13.08%	12.91%	1.20	0.15	
	B		20%	23.89%	23.20%	22.08%	21.18%	20.54%	20.11%	19.84%	19.69%	19.64%	19.67%	19.78%	19.94%	20.16%	20.44%	20.78%	21.14%	21.48%	21.83%	22.16%	1.10	0.24	
Initial Probability Vector obtained from company historic records	C		65%	40.92%	32.74%	29.29%	27.57%	26.56%	25.92%	25.47%	25.14%	24.90%	24.71%	24.57%	24.45%	24.36%	24.29%	24.23%	24.19%	24.16%	24.15%	24.15%	1.00	0.24	
	D		3%	13.25%	17.80%	20.25%	21.75%	22.75%	23.45%	23.93%	24.26%	24.48%	24.62%	24.68%	24.69%	24.65%	24.57%	24.45%	24.31%	24.16%	24.01%	23.86%	0.90	0.21	99.03%
	F		2%	7.00%	9.72%	11.54%	12.87%	13.88%	14.65%	15.23%	15.68%	16.02%	16.29%	16.49%	16.64%	16.75%	16.83%	16.89%	16.92%	16.93%	16.93%	16.92%	0.80	0.14	or Within TARGET
	sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	0.990	
			1.03	1.03	1.02	1.01	1.01	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99			



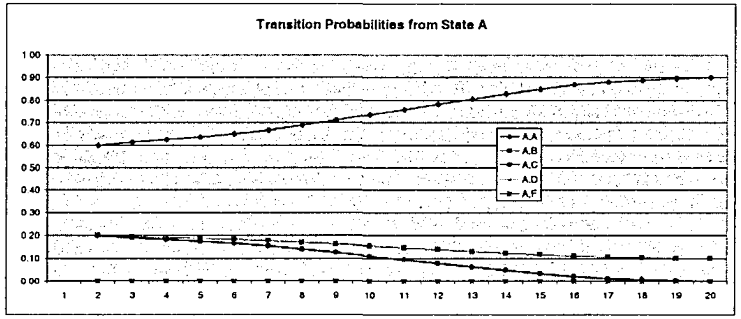
APPENDIX (J)

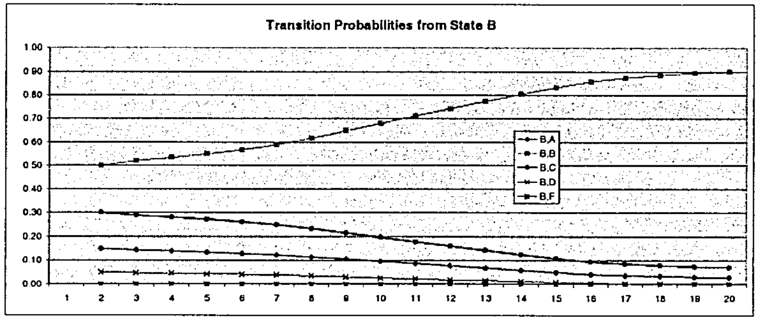
Team Satisfaction Forecasting Update

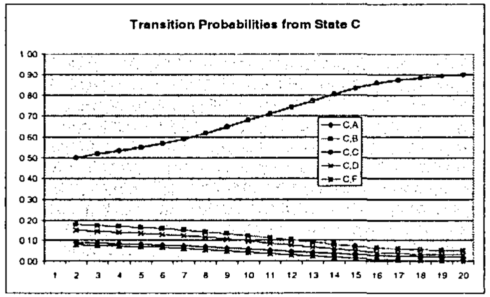
Transition Probabilities as a Function of Project Duration (T)

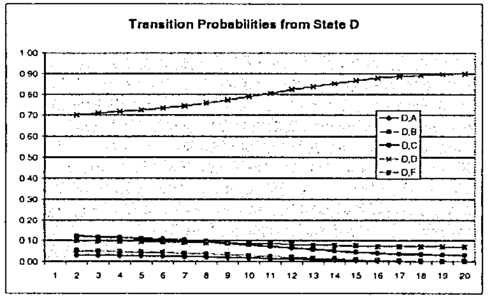
boundary conditions derived based on company historic database

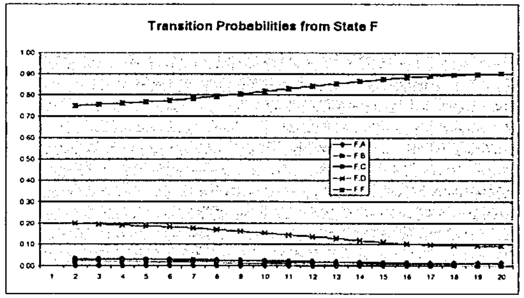
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	0.6000	0.2000	0.2000	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1800	0.5000	0.1500	0.0800	0.0300	0.0500	0.1200	0.7000	0.1000	-	0.0200	0.0300	0.2000	0.7500
5.00	3	at t = 0.15 T	0.6150	0.1950	0.1900	-	-	0.1440	0.5200	0.2885	0.0475	-	0.0865	0.1735	0.5200	0.1440	0.0760	0.0285	0.0475	0.1155	0.7100	0.0985	-	0.0190	0.0290	0.1945	0.7575
8.50	4	at t = 0.20 T	0.6255	0.1915	0.1830	-	-	0.1398	0.5340	0.2805	0.0458	-	0.0841	0.1690	0.5340	0.1398	0.0732	0.0275	0.0458	0.1124	0.7170	0.0975	-	0.0183	0.0283	0.1907	0.7628
12.50	5	at t = 0.25 T	0.6375	0.1875	0.1750	-	-	0.1350	0.5500	0.2713	0.0438	-	0.0813	0.1638	0.5500	0.1350	0.0700	0.0263	0.0438	0.1088	0.7250	0.0963	-	0.0175	0.0275	0.1863	0.7688
17.00	6	at t = 0.30 T	0.6510	0.1830	0.1660	-	-	0.1296	0.5680	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664	0.0249	0.0415	0.1047	0.7340	0.0949	-	0.0166	0.0266	0.1813	0.7755
22.43	7	at t = 0.35 T	0.6673	0.1776	0.1551	-	-	0.1231	0.5897	0.2484	0.0388	-	0.0743	0.1508	0.5897	0.1231	0.0621	0.0233	0.0388	0.0998	0.7449	0.0933	-	0.0155	0.0255	0.1753	0.7836
29.43	8	at t = 0.40 T	0.6883	0.1706	0.1411	-	-	0.1147	0.6177	0.2323	0.0353	-	0.0694	0.1417	0.6177	0.1147	0.0565	0.0212	0.0353	0.0935	0.7589	0.0912	-	0.0141	0.0241	0.1676	0.7941
36.93	9	at t = 0.45 T	0.7108	0.1631	0.1261	-	-	0.1057	0.6477	0.2151	0.0315	-	0.0641	0.1320	0.6477	0.1057	0.0505	0.0189	0.0315	0.0868	0.7739	0.0889	-	0.0126	0.0226	0.1594	0.8054
44.93	10	at t = 0.50 T	0.7348	0.1551	0.1101	-	-	0.0961	0.6797	0.1967	0.0275	-	0.0585	0.1216	0.6797	0.0961	0.0441	0.0165	0.0275	0.0796	0.7899	0.0865	-	0.0110	0.0210	0.1506	0.8174
52.93	11	at t = 0.55 T	0.7588	0.1471	0.0941	-	-	0.0865	0.7117	0.1783	0.0235	-	0.0529	0.1112	0.7117	0.0865	0.0377	0.0141	0.0235	0.0724	0.8059	0.0841	-	0.0094	0.0194	0.1418	0.8294
60.93	12	at t = 0.60 T	0.7828	0.1391	0.0781	-	-	0.0769	0.7437	0.1599	0.0195	-	0.0473	0.1008	0.7437	0.0769	0.0313	0.0117	0.0195	0.0652	0.8219	0.0817	-	0.0078	0.0178	0.1330	0.8414
68.50	13	at t = 0.65 T	0.8055	0.1315	0.0630	-	-	0.0678	0.7740	0.1425	0.0158	-	0.0421	0.0910	0.7740	0.0678	0.0252	0.0095	0.0158	0.0584	0.8370	0.0795	-	0.0063	0.0163	0.1247	0.8528
76.00	14	at t = 0.70 T	0.8280	0.1240	0.0480	-	-	0.0588	0.8040	0.1252	0.0120	-	0.0368	0.0812	0.8040	0.0588	0.0192	0.0072	0.0120	0.0516	0.8520	0.0772	-	0.0048	0.0148	0.1164	0.8640
83.00	15	at t = 0.75 T	0.8490	0.1170	0.0340	-	-	0.0504	0.8320	0.1091	0.0085	-	0.0319	0.0721	0.8320	0.0504	0.0136	0.0051	0.0085	0.0453	0.8660	0.0751	-	0.0034	0.0134	0.1087	0.8745
89.50	16	at t = 0.80 T	0.8685	0.1105	0.0210	-	-	0.0426	0.8580	0.0942	0.0053	-	0.0274	0.0637	0.8580	0.0426	0.0084	0.0032	0.0053	0.0395	0.8790	0.0732	-	0.0021	0.0121	0.1016	0.8843
93.50	17	at t = 0.85 T	0.8805	0.1065	0.0130	-	-	0.0378	0.8740	0.0850	0.0033	-	0.0246	0.0585	0.8740	0.0378	0.0052	0.0020	0.0033	0.0359	0.8870	0.0720	-	0.0013	0.0113	0.0972	0.8903
96.00	18	at t = 0.90 T	0.8880	0.1040	0.0080	-	-	0.0348	0.8840	0.0792	0.0020	-	0.0228	0.0552	0.8840	0.0348	0.0032	0.0012	0.0020	0.0336	0.8920	0.0712	-	0.0008	0.0108	0.0944	0.8940
98.50	19	at t = 0.95 T	0.8955	0.1015	0.0030	-	-	0.0318	0.8940	0.0735	0.0007	-	0.0211	0.0520	0.8940	0.0318	0.0012	0.0004	0.0007	0.0314	0.8970	0.0705	-	0.0003	0.0103	0.0917	0.8978
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0300	0.9000	0.0700	-	-	0.0100	0.0900	0.9000











APPENDIX (J)

Team Satisfaction Forecasting Update

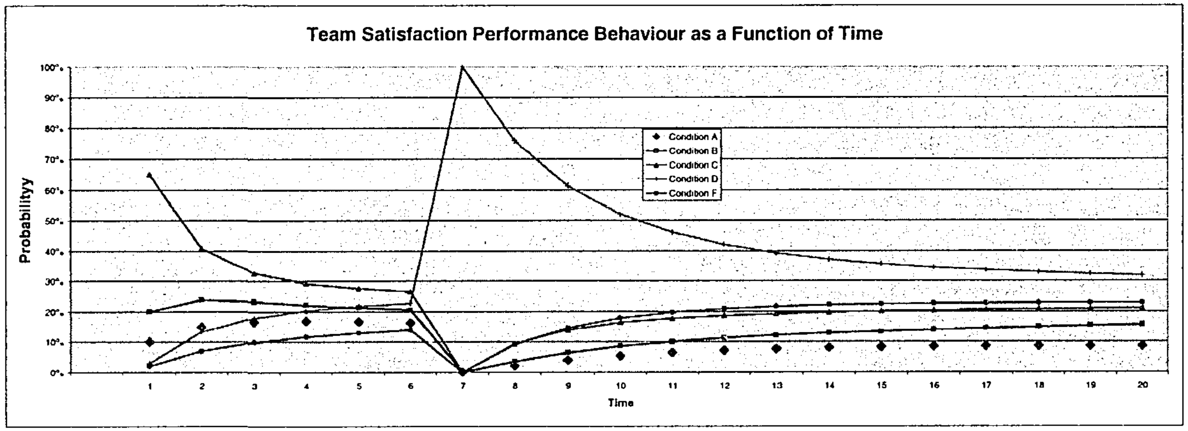
	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.6000**	**0.2000**	**0.2000**	-	-	0.6150	0.1950	0.1900	-	-	0.6255	0.1915	0.1830	-	-	0.6375	0.1875	0.1750	-	-
B						**0.1500**	**0.5000**	**0.3000**	**0.0500**	-	0.1440	0.5200	0.2885	0.0475	-	0.1398	0.5340	0.2805	0.0458	-	0.1350	0.5500	0.2713	0.0438	-
C						**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**	0.0865	0.1735	0.5200	0.1440	0.0760	0.0841	0.1690	0.5340	0.1398	0.0732	0.0813	0.1638	0.5500	0.1350	0.0700
D						**0.0300**	**0.0500**	**0.1200**	**0.7000**	**0.1000**	0.0285	0.0475	0.1155	0.7100	0.0985	0.0275	0.0458	0.1124	0.7170	0.0975	0.0263	0.0438	0.1088	0.7250	0.0963
F						-	**0.0200**	**0.0300**	**0.2000**	**0.7500**	-	0.0190	0.0290	0.1945	0.7575	-	0.0183	0.0283	0.1907	0.7628	-	0.0175	0.0275	0.1863	0.7688

	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6510	0.1830	0.1660	-	-	0.6673	0.1776	0.1551	-	-	0.6883	0.1706	0.1411	-	-	0.7108	0.1631	0.1261	-	-	0.7348	0.1551	0.1101	-	-
B	0.1296	0.5680	0.2609	0.0415	-	0.1231	0.5897	0.2484	0.0388	-	0.1147	0.6177	0.2323	0.0353	-	0.1057	0.6477	0.2151	0.0315	-	0.0961	0.6797	0.1967	0.0275	-
C	0.0781	0.1579	0.5680	0.1296	0.0664	0.0743	0.1508	0.5897	0.1231	0.0621	0.0694	0.1417	0.6177	0.1147	0.0565	0.0641	0.1320	0.6477	0.1057	0.0505	0.0585	0.1216	0.6797	0.0961	0.0441
D	0.0249	0.0415	0.1047	0.7340	0.0949	0.0233	0.0388	0.0998	0.7449	0.0933	0.0212	0.0353	0.0935	0.7589	0.0912	0.0189	0.0315	0.0868	0.7739	0.0889	0.0165	0.0275	0.0796	0.7899	0.0865
F	-	0.0166	0.0266	0.1813	0.7755	-	0.0155	0.0255	0.1753	0.7836	-	0.0141	0.0241	0.1676	0.7941	-	0.0126	0.0226	0.1594	0.8054	-	0.0110	0.0210	0.1506	0.8174

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7588	0.1471	0.0941	-	-	0.7828	0.1391	0.0781	-	-	0.8055	0.1315	0.0630	-	-	0.8280	0.1240	0.0480	-	-	0.8490	0.1170	0.0340	-	-
B	0.0865	0.7117	0.1783	0.0235	-	0.0769	0.7437	0.1599	0.0195	-	0.0678	0.7740	0.1425	0.0158	-	0.0588	0.8040	0.1252	0.0120	-	0.0504	0.8320	0.1091	0.0085	-
C	0.0529	0.1112	0.7117	0.0865	0.0377	0.0473	0.1008	0.7437	0.0769	0.0313	0.0421	0.0910	0.7740	0.0678	0.0252	0.0368	0.0812	0.8040	0.0588	0.0192	0.0319	0.0721	0.8320	0.0504	0.0136
D	0.0141	0.0235	0.0724	0.8059	0.0841	0.0117	0.0195	0.0652	0.8219	0.0817	0.0095	0.0158	0.0584	0.8370	0.0795	0.0072	0.0120	0.0516	0.8520	0.0772	0.0051	0.0085	0.0453	0.8660	0.0751
F	-	0.0094	0.0194	0.1418	0.8294	-	0.0078	0.0178	0.1330	0.8414	-	0.0063	0.0163	0.1247	0.8528	-	0.0048	0.0148	0.1164	0.8640	-	0.0034	0.0134	0.1087	0.8745

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8685	0.1105	0.0210	-	-	0.8805	0.1065	0.0130	-	-	0.8880	0.1040	0.0080	-	-	0.8955	0.1015	0.0030	-	-	**0.9000**	**0.1000**	-	-	-
B	0.0426	0.8580	0.0942	0.0053	-	0.0378	0.8740	0.0850	0.0033	-	0.0348	0.8840	0.0792	0.0020	-	0.0318	0.8940	0.0735	0.0007	-	**0.0300**	**0.9000**	**0.0700**	-	-
C	0.0274	0.0637	0.8580	0.0426	0.0084	0.0246	0.0585	0.8740	0.0378	0.0052	0.0228	0.0552	0.8840	0.0348	0.0032	0.0211	0.0520	0.8940	0.0318	0.0012	**0.0200**	**0.0500**	**0.9000**	**0.0300**	-
D	0.0032	0.0053	0.0395	0.8790	0.0732	0.0020	0.0033	0.0359	0.8870	0.0720	0.0012	0.0020	0.0336	0.8920	0.0712	0.0004	0.0007	0.0314	0.8970	0.0705	-	-	**0.0300**	**0.9000**	**0.0700**
F	-	0.0021	0.0121	0.1016	0.8843	-	0.0013	0.0113	0.0972	0.8903	-	0.0008	0.0108	0.0944	0.8940	-	0.0003	0.0103	0.0917	0.8978	-	-	**0.0100**	**0.0900**	**0.9000**

	Reporting Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Team Satisf Index	Expected Value	The expected team satisfaction performance at the end of the project given the latest actual status is equal to :
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00 T			
	CONDITION	State Prob	State Proba	State Proba	State Proba	State Probabi	State Probat	State Prob	State Proba	State Proba	State Proba	State Prob	State Proba	State Prob	State Proba	State Prob	State Pro	State Pro	State Pro	State Pro	State Proba	TSI	TSI	
	A	10%	14.94%	16.55%	16.83%	16.62%	16.26%	0.00%	2.12%	3.91%	5.31%	6.36%	7.13%	7.68%	8.06%	8.31%	8.45%	8.53%	8.59%	8.62%	8.63%	1.20	0.10	
	B	20%	23.89%	23.20%	22.08%	21.18%	20.54%	0.00%	3.53%	6.37%	8.47%	10.02%	11.18%	12.08%	12.80%	13.41%	13.94%	14.41%	14.85%	15.26%	15.64%	1.10	0.17	
Initial Probability Vector obtained from company historic records	C	65%	40.92%	32.74%	29.29%	27.57%	26.56%	0.00%	9.35%	13.87%	16.30%	17.72%	18.64%	19.27%	19.72%	20.06%	20.33%	20.56%	20.77%	20.95%	21.12%	1.00	0.21	
	D	3%	13.25%	17.80%	20.25%	21.75%	22.75%	100.00%	75.89%	61.28%	52.10%	46.12%	42.09%	39.28%	37.27%	35.79%	34.66%	33.75%	33.00%	32.36%	31.81%	0.90	0.29	95.55%
	F	2%	7.00%	9.72%	11.54%	12.87%	13.88%	0.00%	9.12%	14.56%	17.82%	19.77%	20.96%	21.69%	22.14%	22.43%	22.62%	22.74%	22.80%	22.81%	22.80%	0.80	0.18	or Within TARGET
	sum	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	0.955	
		1.03	1.03	1.02	1.01	1.01	1.00	0.90	0.91	0.92	0.93	0.94	0.94	0.94	0.95	0.95	0.95	0.95	0.95	0.95	0.96			


Team Satisfaction Performance Behaviour as a Function of Time

APPENDIX (J)

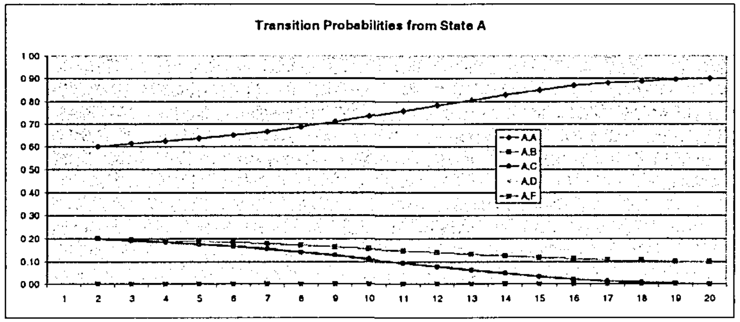
Forecasting Project Performance using Dynamic Markov Chains

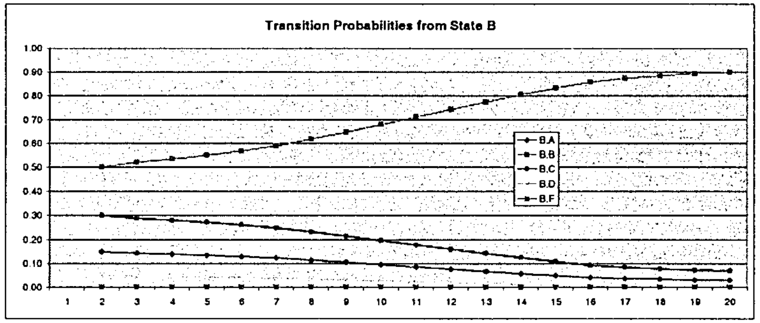
Client Satisfaction Forecasting Model

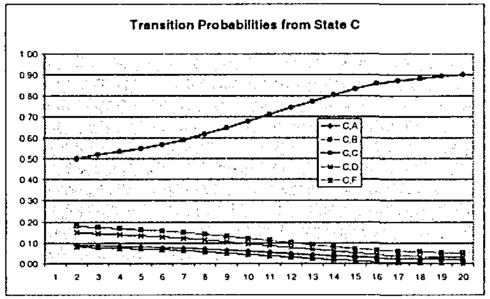
Transition Probabilities as a Function of Project Duration (T)

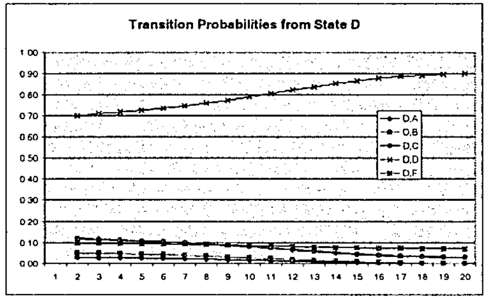
boundary conditions derived based on company historic database

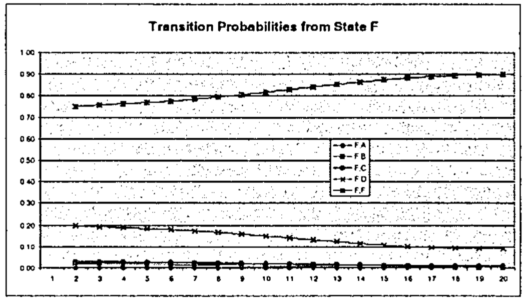
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	**0.6000**	**0.2000**	**0.2000**	-	-	**0.1500**	**0.5000**	**0.3000**	**0.0500**	-	**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**	**0.0300**	**0.0500**	**0.1200**	**0.7000**	**0.1000**	-	**0.0200**	**0.0300**	**0.2000**	**0.7500**
5.00	3	at t = 0.15 T	0.6150	0.1950	0.1900	-	-	0.1440	0.5200	0.2885	0.0475	-	0.0865	0.1735	0.5200	0.1440	0.0760	0.0285	0.0475	0.1155	0.7100	0.0985	-	0.0190	0.0290	0.1945	0.7575
8.50	4	at t = 0.20 T	0.6255	0.1915	0.1830	-	-	0.1398	0.5340	0.2805	0.0458	-	0.0841	0.1690	0.5340	0.1398	0.0732	0.0275	0.0458	0.1124	0.7170	0.0975	-	0.0183	0.0283	0.1907	0.7628
12.50	5	at t = 0.25 T	0.6375	0.1875	0.1750	-	-	0.1350	0.5500	0.2713	0.0438	-	0.0813	0.1638	0.5500	0.1350	0.0700	0.0263	0.0438	0.1088	0.7250	0.0963	-	0.0175	0.0275	0.1863	0.7688
17.00	6	at t = 0.30 T	0.6510	0.1830	0.1660	-	-	0.1296	0.5680	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664	0.0249	0.0415	0.1047	0.7340	0.0949	-	0.0166	0.0266	0.1813	0.7755
22.43	7	at t = 0.35 T	0.6673	0.1776	0.1551	-	-	0.1231	0.5897	0.2484	0.0388	-	0.0743	0.1508	0.5897	0.1231	0.0621	0.0233	0.0388	0.0998	0.7449	0.0933	-	0.0155	0.0255	0.1753	0.7836
29.43	8	at t = 0.40 T	0.6883	0.1706	0.1411	-	-	0.1147	0.6177	0.2323	0.0353	-	0.0694	0.1417	0.6177	0.1147	0.0565	0.0212	0.0353	0.0935	0.7589	0.0912	-	0.0141	0.0241	0.1676	0.7941
36.93	9	at t = 0.45 T	0.7108	0.1631	0.1261	-	-	0.1057	0.6477	0.2151	0.0315	-	0.0641	0.1320	0.6477	0.1057	0.0505	0.0189	0.0315	0.0868	0.7739	0.0889	-	0.0126	0.0226	0.1594	0.8054
44.93	10	at t = 0.50 T	0.7348	0.1551	0.1101	-	-	0.0961	0.6797	0.1967	0.0275	-	0.0585	0.1216	0.6797	0.0961	0.0441	0.0165	0.0275	0.0796	0.7899	0.0865	-	0.0110	0.0210	0.1506	0.8174
52.93	11	at t = 0.55 T	0.7588	0.1471	0.0941	-	-	0.0865	0.7117	0.1783	0.0235	-	0.0529	0.1112	0.7117	0.0865	0.0377	0.0141	0.0235	0.0724	0.8059	0.0841	-	0.0094	0.0194	0.1418	0.8294
60.93	12	at t = 0.60 T	0.7828	0.1391	0.0781	-	-	0.0769	0.7437	0.1599	0.0195	-	0.0473	0.1008	0.7437	0.0769	0.0313	0.0117	0.0195	0.0652	0.8219	0.0817	-	0.0078	0.0178	0.1330	0.8414
68.50	13	at t = 0.65 T	0.8055	0.1315	0.0630	-	-	0.0678	0.7740	0.1425	0.0158	-	0.0421	0.0910	0.7740	0.0678	0.0252	0.0095	0.0158	0.0584	0.8370	0.0795	-	0.0063	0.0163	0.1247	0.8528
76.00	14	at t = 0.70 T	0.8280	0.1240	0.0480	-	-	0.0588	0.8040	0.1252	0.0120	-	0.0368	0.0812	0.8040	0.0588	0.0192	0.0072	0.0120	0.0516	0.8520	0.0772	-	0.0048	0.0148	0.1164	0.8640
83.00	15	at t = 0.75 T	0.8490	0.1170	0.0340	-	-	0.0504	0.8320	0.1091	0.0085	-	0.0319	0.0721	0.8320	0.0504	0.0136	0.0051	0.0085	0.0453	0.8660	0.0751	-	0.0034	0.0134	0.1087	0.8745
89.50	16	at t = 0.80 T	0.8685	0.1105	0.0210	-	-	0.0426	0.8580	0.0942	0.0053	-	0.0274	0.0637	0.8580	0.0426	0.0084	0.0032	0.0053	0.0395	0.8790	0.0732	-	0.0021	0.0121	0.1016	0.8843
93.50	17	at t = 0.85 T	0.8805	0.1065	0.0130	-	-	0.0378	0.8740	0.0850	0.0033	-	0.0246	0.0585	0.8740	0.0378	0.0052	0.0020	0.0033	0.0359	0.8870	0.0720	-	0.0013	0.0113	0.0972	0.8903
96.00	18	at t = 0.90 T	0.8880	0.1040	0.0080	-	-	0.0348	0.8840	0.0792	0.0020	-	0.0228	0.0552	0.8840	0.0348	0.0032	0.0012	0.0020	0.0336	0.8920	0.0712	-	0.0008	0.0108	0.0944	0.8940
98.50	19	at t = 0.95 T	0.8955	0.1015	0.0030	-	-	0.0318	0.8940	0.0735	0.0007	-	0.0211	0.0520	0.8940	0.0318	0.0012	0.0004	0.0007	0.0314	0.8970	0.0705	-	0.0003	0.0103	0.0917	0.8978
100.00	20	at t = 1.00 T	**0.9000**	**0.1000**	-	-	-	**0.0300**	**0.9000**	**0.0700**	-	-	**0.0200**	**0.0500**	**0.9000**	**0.0300**	-	-	-	**0.0300**	**0.9000**	**0.0700**	-	-	**0.0100**	**0.0900**	**0.9000**


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Client Satisfaction Forecasting Model

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.6000**	**0.2000**	**0.2000**	-	-	0.6150	0.1950	0.1900	-	-	0.6255	0.1915	0.1830	-	-	0.6375	0.1875	0.1750	-	-
B						**0.1500**	**0.5000**	**0.3000**	**0.0500**	-	0.1440	0.5200	0.2885	0.0475	-	0.1398	0.5340	0.2805	0.0458	-	0.1350	0.5500	0.2713	0.0438	-
C						**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**	0.0865	0.1735	0.5200	0.1440	0.0760	0.0841	0.1690	0.5340	0.1398	0.0732	0.0813	0.1638	0.5500	0.1350	0.0700
D						**0.0300**	**0.0500**	**0.1200**	**0.7000**	**0.1000**	0.0285	0.0475	0.1155	0.7100	0.0985	0.0275	0.0458	0.1124	0.7170	0.0975	0.0263	0.0438	0.1088	0.7250	0.0963
F						-	**0.0200**	**0.0300**	**0.2000**	**0.7500**	-	0.0190	0.0290	0.1945	0.7575	-	0.0183	0.0283	0.1907	0.7628	-	0.0175	0.0275	0.1863	0.7688

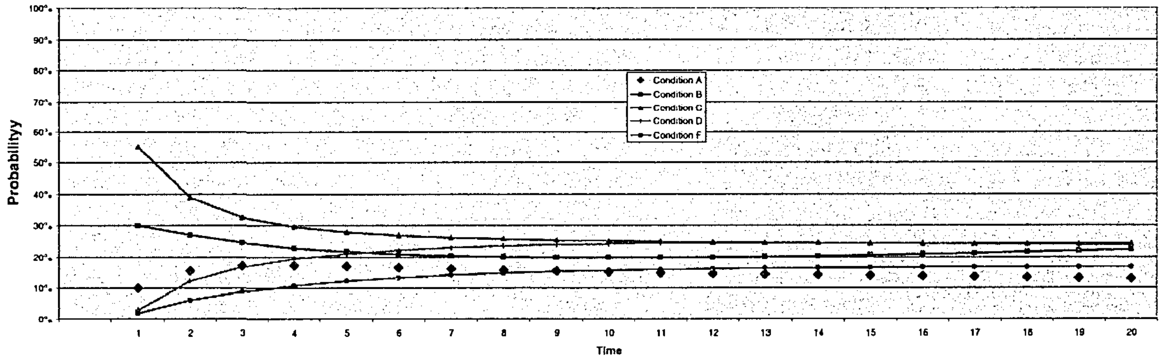
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6510	0.1830	0.1660	-	-	0.6673	0.1776	0.1551	-	-	0.6883	0.1706	0.1411	-	-	0.7108	0.1631	0.1261	-	-	0.7348	0.1551	0.1101	-	-
B	0.1296	0.5680	0.2609	0.0415	-	0.1231	0.5897	0.2484	0.0388	-	0.1147	0.6177	0.2323	0.0353	-	0.1057	0.6477	0.2151	0.0315	-	0.0961	0.6797	0.1967	0.0275	-
C	0.0781	0.1579	0.5680	0.1296	0.0664	0.0743	0.1508	0.5897	0.1231	0.0621	0.0694	0.1417	0.6177	0.1147	0.0565	0.0641	0.1320	0.6477	0.1057	0.0505	0.0585	0.1216	0.6797	0.0961	0.0441
D	0.0249	0.0415	0.1047	0.7340	0.0949	0.0233	0.0388	0.0998	0.7449	0.0933	0.0212	0.0353	0.0935	0.7589	0.0912	0.0189	0.0315	0.0868	0.7739	0.0889	0.0165	0.0275	0.0796	0.7899	0.0865
F	-	0.0166	0.0266	0.1813	0.7755	-	0.0155	0.0255	0.1753	0.7836	-	0.0141	0.0241	0.1676	0.7941	-	0.0126	0.0226	0.1594	0.8054	-	0.0110	0.0210	0.1506	0.8174

	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7588	0.1471	0.0941	-	-	0.7828	0.1391	0.0781	-	-	0.8055	0.1315	0.0630	-	-	0.8280	0.1240	0.0480	-	-	0.8490	0.1170	0.0340	-	-
B	0.0865	0.7117	0.1783	0.0235	-	0.0769	0.7437	0.1599	0.0195	-	0.0678	0.7740	0.1425	0.0158	-	0.0588	0.8040	0.1252	0.0120	-	0.0504	0.8320	0.1091	0.0085	-
C	0.0529	0.1112	0.7117	0.0865	0.0377	0.0473	0.1008	0.7437	0.0769	0.0313	0.0421	0.0910	0.7740	0.0678	0.0252	0.0368	0.0812	0.8040	0.0588	0.0192	0.0319	0.0721	0.8320	0.0504	0.0136
D	0.0141	0.0235	0.0724	0.8059	0.0841	0.0117	0.0195	0.0652	0.8219	0.0817	0.0095	0.0158	0.0584	0.8370	0.0795	0.0072	0.0120	0.0516	0.8520	0.0772	0.0051	0.0085	0.0453	0.8660	0.0751
F	-	0.0094	0.0194	0.1418	0.8294	-	0.0078	0.0178	0.1330	0.8414	-	0.0063	0.0163	0.1247	0.8528	-	0.0048	0.0148	0.1164	0.8640	-	0.0034	0.0134	0.1087	0.8745

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8685	0.1105	0.0210	-	-	0.8805	0.1065	0.0130	-	-	0.8880	0.1040	0.0080	-	-	0.8955	0.1015	0.0030	-	-	**0.9000**	**0.1000**	-	-	-
B	0.0426	0.8580	0.0942	0.0053	-	0.0378	0.8740	0.0850	0.0033	-	0.0348	0.8840	0.0792	0.0020	-	0.0318	0.8940	0.0735	0.0007	-	**0.0300**	**0.9000**	**0.0700**	-	-
C	0.0274	0.0637	0.8580	0.0426	0.0084	0.0246	0.0585	0.8740	0.0378	0.0052	0.0228	0.0552	0.8840	0.0348	0.0032	0.0211	0.0520	0.8940	0.0318	0.0012	**0.0200**	**0.0500**	**0.9000**	**0.0300**	-
D	0.0032	0.0053	0.0395	0.8790	0.0732	0.0020	0.0033	0.0359	0.8870	0.0720	0.0012	0.0020	0.0336	0.8920	0.0712	0.0004	0.0007	0.0314	0.8970	0.0705	-	-	**0.0300**	**0.9000**	**0.0700**
F	-	0.0021	0.0121	0.1016	0.8843	-	0.0013	0.0113	0.0972	0.8903	-	0.0008	0.0108	0.0944	0.8940	-	0.0003	0.0103	0.0917	0.8978	-	-	**0.0100**	**0.0900**	**0.9000**

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	lient Satis Index	Expected Value	The expected client satisfaction performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	t = 0.80	t = 0.85	t = 0.90	t = 0.95	at t = 1.00 T			
	CONDITION		State Prob	State Proba	State Proba	State Proba	State Probabi	State Probal	State Proba	State Prob	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Pro	State Pro	State Pro	State Pro	State Proba	CSI	CSI	
	A		**10%**	15.54%	17.17%	17.38%	17.08%	16.63%	16.19%	15.79%	15.44%	**15.14%**	**14.87%**	**14.63%**	**14.41%**	**14.19%**	**13.98%**	13.76%	13.55%	13.36%	13.17%	13.00%	1.20	0.16	
	B		**30%**	27.09%	24.57%	22.85%	21.71%	20.94%	20.43%	20.10%	19.92%	**19.84%**	**19.86%**	**19.94%**	**20.10%**	**20.31%**	**20.59%**	20.93%	21.28%	21.62%	21.97%	22.30%	1.10	0.25	
Initial Probability Vector obtained from company historic records	C		**55%**	38.92%	32.60%	29.58%	27.92%	26.89%	26.19%	25.70%	25.34%	**25.07%**	**24.86%**	**24.70%**	**24.58%**	**24.47%**	**24.39%**	24.32%	24.27%	24.24%	24.23%	24.23%	1.00	0.24	
	D		3%	12.25%	16.79%	19.41%	21.08%	22.20%	23.00%	23.56%	23.95%	**24.21%**	**24.37%**	**24.46%**	**24.49%**	**24.47%**	**24.39%**	24.28%	24.15%	24.01%	23.86%	23.71%	0.90	0.21	**99.10%**
	F		2%	6.20%	8.86%	10.78%	12.23%	13.34%	14.19%	14.84%	15.35%	**15.73%**	**16.03%**	**16.26%**	**16.43%**	**16.56%**	**16.65%**	16.71%	16.75%	16.77%	16.78%	16.77%	0.80	0.13	or Within TARGET
	sum		**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	Total	0.991	
			1.04	1.03	1.02	1.02	1.01	1.01	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99			

Client Satisfaction Performance Behaviour as a Function of Time



APPENDIX (J)

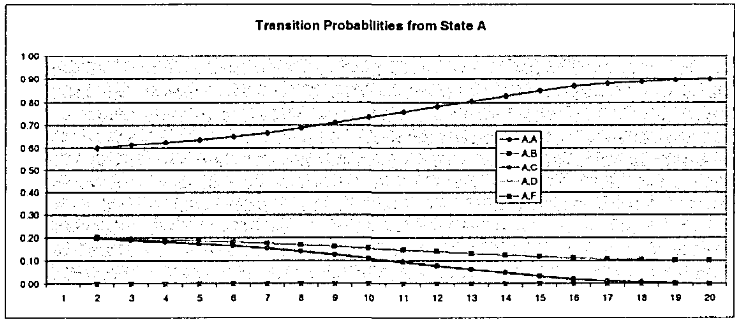
Forecasting Project Performance using Dynamic Markov Chains

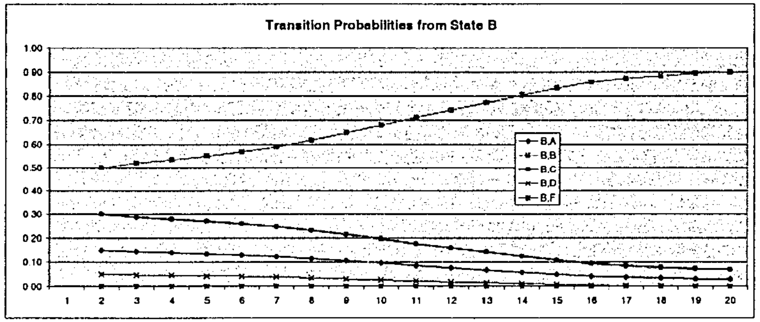
Client Satisfaction Forecasting Update

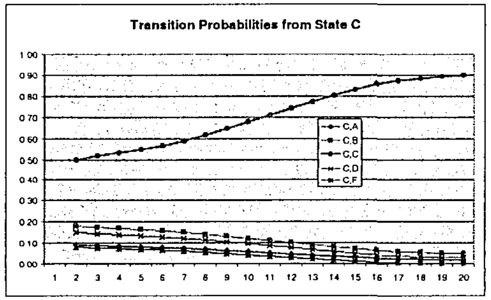
Transition Probabilities as a Function of Project Duration (T)

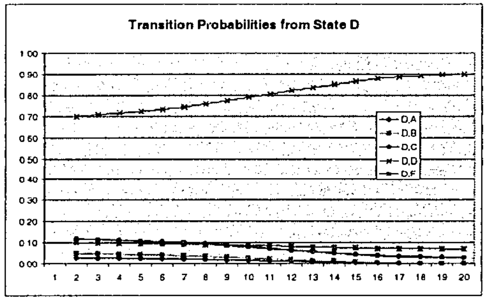
boundary conditions derived based on company historic database

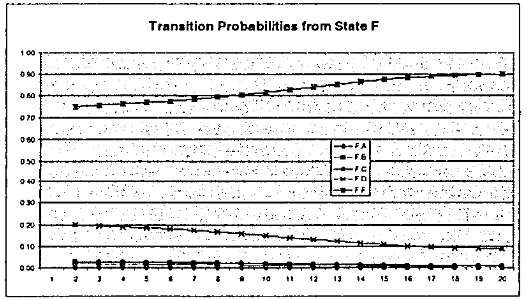
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	0.6000	0.2000	0.2000	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1800	0.5000	0.1500	0.0800	0.0300	0.0500	0.1200	0.7000	0.1000	-	0.0200	0.0300	0.2000	0.7500
5.00	3	at t = 0.15 T	0.6150	0.1950	0.1900	-	-	0.1440	0.5200	0.2885	0.0475	-	0.0865	0.1735	0.5200	0.1440	0.0760	0.0285	0.0475	0.1155	0.7100	0.0985	-	0.0190	0.0290	0.1945	0.7575
8.50	4	at t = 0.20 T	0.6255	0.1915	0.1830	-	-	0.1398	0.5340	0.2805	0.0458	-	0.0841	0.1690	0.5340	0.1398	0.0732	0.0275	0.0458	0.1124	0.7170	0.0975	-	0.0183	0.0283	0.1907	0.7628
12.50	5	at t = 0.25 T	0.6375	0.1875	0.1750	-	-	0.1350	0.5500	0.2713	0.0438	-	0.0813	0.1638	0.5500	0.1350	0.0700	0.0263	0.0438	0.1088	0.7250	0.0963	-	0.0175	0.0275	0.1863	0.7688
17.00	6	at t = 0.30 T	0.6510	0.1830	0.1660	-	-	0.1296	0.5680	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664	0.0249	0.0415	0.1047	0.7340	0.0949	-	0.0166	0.0266	0.1813	0.7755
22.43	7	at t = 0.35 T	0.6673	0.1776	0.1551	-	-	0.1231	0.5897	0.2484	0.0388	-	0.0743	0.1508	0.5897	0.1231	0.0621	0.0233	0.0388	0.0998	0.7449	0.0933	-	0.0155	0.0255	0.1753	0.7836
29.43	8	at t = 0.40 T	0.6883	0.1706	0.1411	-	-	0.1147	0.6177	0.2323	0.0353	-	0.0694	0.1417	0.6177	0.1147	0.0565	0.0212	0.0353	0.0935	0.7589	0.0912	-	0.0141	0.0241	0.1676	0.7941
36.93	9	at t = 0.45 T	0.7108	0.1631	0.1261	-	-	0.1057	0.6477	0.2151	0.0315	-	0.0641	0.1320	0.6477	0.1057	0.0505	0.0189	0.0315	0.0868	0.7739	0.0889	-	0.0126	0.0226	0.1594	0.8054
44.93	10	at t = 0.50 T	0.7348	0.1551	0.1101	-	-	0.0961	0.6797	0.1967	0.0275	-	0.0585	0.1216	0.6797	0.0961	0.0441	0.0165	0.0275	0.0796	0.7899	0.0865	-	0.0110	0.0210	0.1506	0.8174
52.93	11	at t = 0.55 T	0.7588	0.1471	0.0941	-	-	0.0865	0.7117	0.1783	0.0235	-	0.0529	0.1112	0.7117	0.0865	0.0377	0.0141	0.0235	0.0724	0.8059	0.0841	-	0.0094	0.0194	0.1418	0.8294
60.93	12	at t = 0.60 T	0.7828	0.1391	0.0781	-	-	0.0769	0.7437	0.1599	0.0195	-	0.0473	0.1008	0.7437	0.0769	0.0313	0.0117	0.0195	0.0652	0.8219	0.0817	-	0.0078	0.0178	0.1330	0.8414
68.50	13	at t = 0.65 T	0.8055	0.1315	0.0630	-	-	0.0678	0.7740	0.1425	0.0158	-	0.0421	0.0910	0.7740	0.0678	0.0252	0.0095	0.0158	0.0584	0.8370	0.0795	-	0.0063	0.0163	0.1247	0.8528
76.00	14	at t = 0.70 T	0.8280	0.1240	0.0480	-	-	0.0588	0.8040	0.1252	0.0120	-	0.0368	0.0812	0.8040	0.0588	0.0192	0.0072	0.0120	0.0516	0.8520	0.0772	-	0.0048	0.0148	0.1164	0.8640
83.00	15	at t = 0.75 T	0.8490	0.1170	0.0340	-	-	0.0504	0.8320	0.1091	0.0085	-	0.0319	0.0721	0.8320	0.0504	0.0136	0.0051	0.0085	0.0453	0.8660	0.0751	-	0.0034	0.0134	0.1087	0.8745
89.50	16	at t = 0.80 T	0.8685	0.1105	0.0210	-	-	0.0426	0.8580	0.0942	0.0053	-	0.0274	0.0637	0.8580	0.0426	0.0084	0.0032	0.0053	0.0395	0.8790	0.0732	-	0.0021	0.0121	0.1016	0.8843
93.50	17	at t = 0.85 T	0.8805	0.1065	0.0130	-	-	0.0378	0.8740	0.0850	0.0033	-	0.0246	0.0585	0.8740	0.0378	0.0052	0.0020	0.0033	0.0359	0.8870	0.0720	-	0.0013	0.0113	0.0972	0.8903
96.00	18	at t = 0.90 T	0.8880	0.1040	0.0080	-	-	0.0348	0.8840	0.0792	0.0020	-	0.0228	0.0552	0.8840	0.0348	0.0032	0.0012	0.0020	0.0336	0.8920	0.0712	-	0.0008	0.0108	0.0944	0.8940
98.50	19	at t = 0.95 T	0.8955	0.1015	0.0030	-	-	0.0318	0.8940	0.0735	0.0007	-	0.0211	0.0520	0.8940	0.0318	0.0012	0.0004	0.0007	0.0314	0.8970	0.0705	-	0.0003	0.0103	0.0917	0.8978
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0300	0.9000	0.0700	-	-	0.0100	0.0900	0.9000


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Client Satisfaction Forecasting Update

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						**0.6000**	**0.2000**	**0.2000**	**-**	**-**	0.6150	0.1950	0.1900	-	-	0.6255	0.1915	0.1830	-	-	0.6375	0.1875	0.1750	-	-
B						**0.1500**	**0.5000**	**0.3000**	**0.0500**	**-**	0.1440	0.5200	0.2885	0.0475	-	0.1398	0.5340	0.2805	0.0458	-	0.1350	0.5500	0.2713	0.0438	-
C						**0.0900**	**0.1800**	**0.5000**	**0.1500**	**0.0800**	0.0865	0.1735	0.5200	0.1440	0.0760	0.0841	0.1690	0.5340	0.1398	0.0732	0.0813	0.1638	0.5500	0.1350	0.0700
D						**0.0300**	**0.0500**	**0.1200**	**0.7000**	**0.1000**	0.0285	0.0475	0.1155	0.7100	0.0985	0.0275	0.0458	0.1124	0.7170	0.0975	0.0263	0.0438	0.1088	0.7250	0.0963
F						**-**	**0.0200**	**0.0300**	**0.2000**	**0.7500**	-	0.0190	0.0290	0.1945	0.7575	-	0.0183	0.0283	0.1907	0.7628	-	0.0175	0.0275	0.1863	0.7688

	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6510	0.1830	0.1660	-	-	0.6673	0.1776	0.1551	-	-	0.6883	0.1706	0.1411	-	-	0.7108	0.1631	0.1261	-	-	0.7348	0.1551	0.1101	-	-
B	0.1296	0.5680	0.2609	0.0415	-	0.1231	0.5897	0.2484	0.0388	-	0.1147	0.6177	0.2323	0.0353	-	0.1057	0.6477	0.2151	0.0315	-	0.0961	0.6797	0.1967	0.0275	-
C	0.0781	0.1579	0.5680	0.1296	0.0664	0.0743	0.1508	0.5897	0.1231	0.0621	0.0694	0.1417	0.6177	0.1147	0.0565	0.0641	0.1320	0.6477	0.1057	0.0505	0.0585	0.1216	0.6797	0.0961	0.0441
D	0.0249	0.0415	0.1047	0.7340	0.0949	0.0233	0.0388	0.0998	0.7449	0.0933	0.0212	0.0353	0.0935	0.7589	0.0912	0.0189	0.0315	0.0868	0.7739	0.0889	0.0165	0.0275	0.0796	0.7899	0.0865
F	-	0.0166	0.0266	0.1813	0.7755	-	0.0155	0.0255	0.1753	0.7836	-	0.0141	0.0241	0.1676	0.7941	-	0.0126	0.0226	0.1594	0.8054	-	0.0110	0.0210	0.1506	0.8174

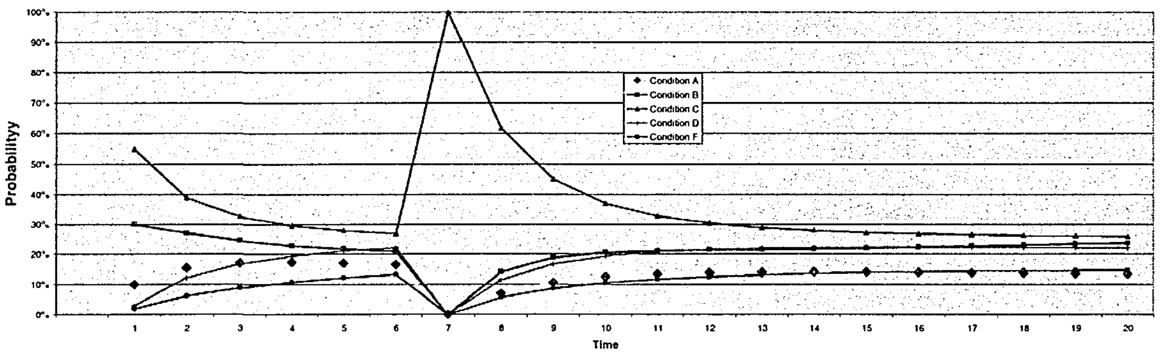
	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7588	0.1471	0.0941	-	-	0.7828	0.1391	0.0781	-	-	0.8055	0.1315	0.0630	-	-	0.8280	0.1240	0.0480	-	-	0.8490	0.1170	0.0340	-	-
B	0.0865	0.7117	0.1783	0.0235	-	0.0769	0.7437	0.1599	0.0195	-	0.0678	0.7740	0.1425	0.0158	-	0.0588	0.8040	0.1252	0.0120	-	0.0504	0.8320	0.1091	0.0085	-
C	0.0529	0.1112	0.7117	0.0865	0.0377	0.0473	0.1008	0.7437	0.0769	0.0313	0.0421	0.0910	0.7740	0.0678	0.0252	0.0368	0.0812	0.8040	0.0588	0.0192	0.0319	0.0721	0.8320	0.0504	0.0136
D	0.0141	0.0235	0.0724	0.8059	0.0841	0.0117	0.0195	0.0652	0.8219	0.0817	0.0095	0.0158	0.0584	0.8370	0.0795	0.0072	0.0120	0.0516	0.8520	0.0772	0.0051	0.0085	0.0453	0.8660	0.0751
F	-	0.0094	0.0194	0.1418	0.8294	-	0.0078	0.0178	0.1330	0.8414	-	0.0063	0.0163	0.1247	0.8528	-	0.0048	0.0148	0.1164	0.8640	-	0.0034	0.0134	0.1087	0.8745

	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8685	0.1105	0.0210	-	-	0.8805	0.1065	0.0130	-	-	0.8880	0.1040	0.0080	-	-	0.8955	0.1015	0.0030	-	-	**0.9600**	**0.1000**	**-**	**-**	**-**
B	0.0426	0.8580	0.0942	0.0053	-	0.0378	0.8740	0.0850	0.0033	-	0.0348	0.8840	0.0792	0.0020	-	0.0318	0.8940	0.0735	0.0007	-	**0.0300**	**0.9000**	**0.0700**	**-**	**-**
C	0.0274	0.0637	0.8580	0.0426	0.0084	0.0246	0.0585	0.8740	0.0378	0.0052	0.0228	0.0552	0.8840	0.0348	0.0032	0.0211	0.0520	0.8940	0.0318	0.0012	**0.0200**	**0.0500**	**0.9000**	**0.0300**	**-**
D	0.0032	0.0053	0.0395	0.8790	0.0732	0.0020	0.0033	0.0359	0.8870	0.0720	0.0012	0.0020	0.0336	0.8920	0.0712	0.0004	0.0007	0.0314	0.8970	0.0705	**-**	**-**	**0.0300**	**0.9000**	**0.0700**
F	-	0.0021	0.0121	0.1016	0.8843	-	0.0013	0.0113	0.0972	0.8903	-	0.0008	0.0108	0.0944	0.8940	-	0.0003	0.0103	0.0917	0.8978	**-**	**-**	**0.0100**	**0.0900**	**0.9000**

Initial Probability Vector obtained from company historic records

Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Client Satisf	Expected	The expected client satisfaction performance at the end of the project given the latest actual status is equal to :
		at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80	at t = 0.85	at t = 0.90	at t = 0.95	at t = 1.00 T	Index	Value	
CONDITION		State Proba	State Proba	State Proba	State Proba	State Probabi	State Probal	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Proba	State Prol	State Prol	State Prol	State Prol	State Proba	CSI	CSI	
A		**10%**	15.54%	17.17%	17.38%	17.08%	16.63%	0.00%	6.94%	10.61%	**12.53%**	**13.51%**	**14.00%**	**14.21%**	**14.26%**	**14.21%**	14.10%	13.96%	13.82%	13.67%	13.53%	1.20	0.16	
B		**30%**	27.09%	24.57%	22.85%	21.71%	20.94%	0.00%	14.17%	18.90%	**20.53%**	**21.12%**	**21.39%**	**21.58%**	**21.79%**	**22.05%**	22.38%	22.72%	23.06%	23.40%	23.73%	1.10	0.26	
C		**55%**	38.92%	32.60%	29.58%	27.92%	26.89%	**100.00%**	61.77%	45.06%	**37.03%**	**32.80%**	**30.39%**	**28.92%**	**27.97%**	**27.32%**	26.87%	26.53%	26.27%	26.07%	25.91%	1.00	0.26	
D		**3%**	12.25%	16.79%	19.41%	21.08%	22.20%	0.00%	11.47%	16.75%	**19.39%**	**20.80%**	**21.59%**	**22.05%**	**22.28%**	**22.38%**	22.38%	22.32%	22.25%	22.15%	22.04%	0.90	0.20	**99.92%**
F		**2%**	6.20%	8.86%	10.78%	12.23%	13.34%	0.00%	5.65%	8.68%	**10.53%**	**11.76%**	**12.62%**	**13.24%**	**13.70%**	**14.03%**	14.28%	14.46%	14.60%	14.71%	14.79%	0.80	0.12	or Within TARGET
sum		**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	Total	0.999	
		1.04	1.03	1.02	1.02	1.01	1.01	1.00	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00			

Client Satisfaction Performance Behaviour as a Function of Time



APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

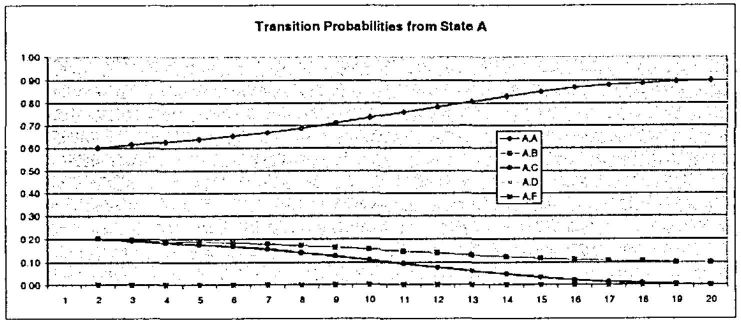
Client Satisfaction Forecasting Update-Scenario 1

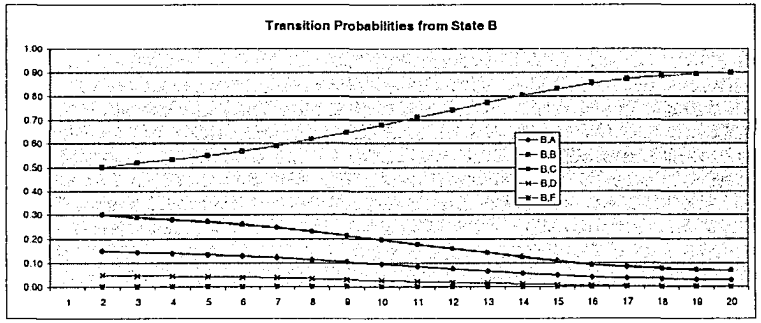
MODEL UPDATE AS AT T-15

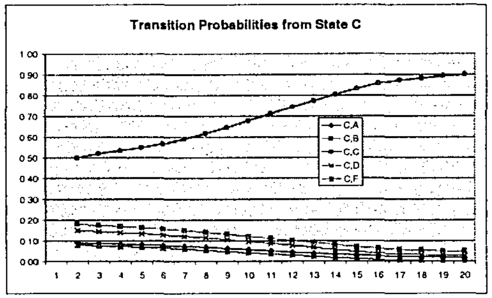
Transition Probabilities as a Function of Project Duration (T)

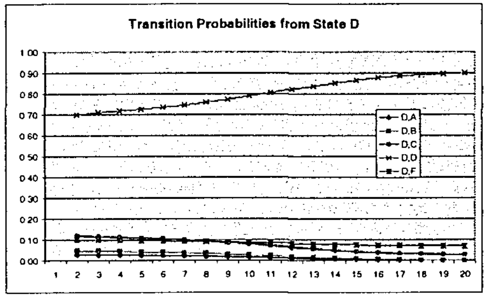
boundary conditions derived based on company historic database

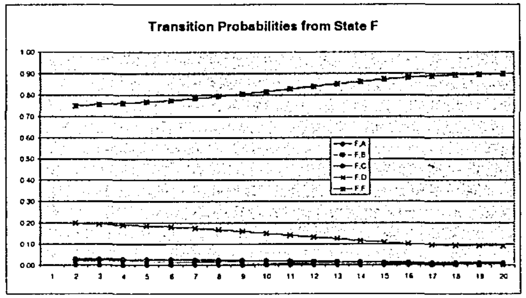
S-Curve By Mhrs	Period		(A,A)	(A,B)	(A,C)	(A,D)	(A,F)	(B,A)	(B,B)	(B,C)	(B,D)	(B,F)	(C,A)	(C,B)	(C,C)	(C,D)	(C,F)	(D,A)	(D,B)	(D,C)	(D,D)	(D,F)	(F,A)	(F,B)	(F,C)	(F,D)	(F,F)
1.00	1	at t = 0.05 T																									
2.50	2	at t = 0.10 T	0.6000	0.2000	0.2000	-	-	0.1500	0.5000	0.3000	0.0500	-	0.0900	0.1800	0.5000	0.1500	0.0800	0.0300	0.0500	0.1200	0.7000	0.1000	-	0.0200	0.0300	0.2000	0.7500
5.00	3	at t = 0.15 T	0.6150	0.1950	0.1900	-	-	0.1440	0.5200	0.2885	0.0475	-	0.0865	0.1735	0.5200	0.1440	0.0760	0.0285	0.0475	0.1155	0.7100	0.0985	-	0.0190	0.0290	0.1945	0.7575
8.50	4	at t = 0.20 T	0.6255	0.1915	0.1830	-	-	0.1398	0.5340	0.2805	0.0458	-	0.0841	0.1690	0.5340	0.1398	0.0732	0.0275	0.0458	0.1124	0.7170	0.0975	-	0.0183	0.0283	0.1907	0.7628
12.50	5	at t = 0.25 T	0.6375	0.1875	0.1750	-	-	0.1350	0.5500	0.2713	0.0438	-	0.0813	0.1638	0.5500	0.1350	0.0700	0.0263	0.0438	0.1088	0.7250	0.0963	-	0.0175	0.0275	0.1863	0.7688
17.00	6	at t = 0.30 T	0.6510	0.1830	0.1660	-	-	0.1296	0.5680	0.2609	0.0415	-	0.0781	0.1579	0.5680	0.1296	0.0664	0.0249	0.0415	0.1047	0.7340	0.0949	-	0.0166	0.0266	0.1813	0.7755
22.43	7	at t = 0.35 T	0.6673	0.1776	0.1551	-	-	0.1231	0.5897	0.2484	0.0388	-	0.0743	0.1508	0.5897	0.1231	0.0621	0.0233	0.0388	0.0998	0.7449	0.0933	-	0.0155	0.0255	0.1753	0.7836
29.43	8	at t = 0.40 T	0.6883	0.1706	0.1411	-	-	0.1147	0.6177	0.2323	0.0353	-	0.0694	0.1417	0.6177	0.1147	0.0565	0.0212	0.0353	0.0935	0.7589	0.0912	-	0.0141	0.0241	0.1676	0.7941
36.93	9	at t = 0.45 T	0.7108	0.1631	0.1261	-	-	0.1057	0.6477	0.2151	0.0315	-	0.0641	0.1320	0.6477	0.1057	0.0505	0.0189	0.0315	0.0868	0.7739	0.0889	-	0.0126	0.0226	0.1594	0.8054
44.93	10	at t = 0.50 T	0.7348	0.1551	0.1101	-	-	0.0961	0.6797	0.1967	0.0275	-	0.0585	0.1216	0.6797	0.0961	0.0441	0.0165	0.0275	0.0796	0.7899	0.0865	-	0.0110	0.0210	0.1506	0.8174
52.93	11	at t = 0.55 T	0.7588	0.1471	0.0941	-	-	0.0865	0.7117	0.1783	0.0235	-	0.0529	0.1112	0.7117	0.0865	0.0377	0.0141	0.0235	0.0724	0.8059	0.0841	-	0.0094	0.0194	0.1418	0.8294
60.93	12	at t = 0.60 T	0.7828	0.1391	0.0781	-	-	0.0769	0.7437	0.1599	0.0195	-	0.0473	0.1008	0.7437	0.0769	0.0313	0.0117	0.0195	0.0652	0.8219	0.0817	-	0.0078	0.0178	0.1330	0.8414
68.50	13	at t = 0.65 T	0.8055	0.1315	0.0630	-	-	0.0678	0.7740	0.1425	0.0158	-	0.0421	0.0910	0.7740	0.0678	0.0252	0.0095	0.0158	0.0584	0.8370	0.0795	-	0.0063	0.0163	0.1247	0.8528
76.00	14	at t = 0.70 T	0.8280	0.1240	0.0480	-	-	0.0588	0.8040	0.1252	0.0120	-	0.0368	0.0812	0.8040	0.0588	0.0192	0.0072	0.0120	0.0516	0.8520	0.0772	-	0.0048	0.0148	0.1164	0.8640
83.00	15	at t = 0.75 T	0.8490	0.1170	0.0340	-	-	0.0504	0.8320	0.1091	0.0085	-	0.0319	0.0721	0.8320	0.0504	0.0136	0.0051	0.0085	0.0453	0.8660	0.0751	-	0.0034	0.0134	0.1087	0.8745
89.50	16	at t = 0.80 T	0.8685	0.1105	0.0210	-	-	0.0426	0.8580	0.0942	0.0053	-	0.0274	0.0637	0.8580	0.0426	0.0084	0.0032	0.0053	0.0395	0.8790	0.0732	-	0.0021	0.0121	0.1016	0.8843
93.50	17	at t = 0.85 T	0.8805	0.1065	0.0130	-	-	0.0378	0.8740	0.0850	0.0033	-	0.0246	0.0585	0.8740	0.0378	0.0052	0.0020	0.0033	0.0359	0.8870	0.0720	-	0.0013	0.0113	0.0972	0.8903
96.00	18	at t = 0.90 T	0.8880	0.1040	0.0080	-	-	0.0348	0.8840	0.0792	0.0020	-	0.0228	0.0552	0.8840	0.0348	0.0032	0.0012	0.0020	0.0336	0.8920	0.0712	-	0.0008	0.0108	0.0944	0.8940
98.50	19	at t = 0.95 T	0.8955	0.1015	0.0030	-	-	0.0318	0.8940	0.0735	0.0007	-	0.0211	0.0520	0.8940	0.0318	0.0012	0.0004	0.0007	0.0314	0.8970	0.0705	-	0.0003	0.0103	0.0917	0.8978
100.00	20	at t = 1.00 T	0.9000	0.1000	-	-	-	0.0300	0.9000	0.0700	-	-	0.0200	0.0500	0.9000	0.0300	-	-	-	0.0300	0.9000	0.0700	-	-	0.0100	0.0900	0.9000


Transition Probabilities from State A


Transition Probabilities from State B


Transition Probabilities from State C


Transition Probabilities from State D


Transition Probabilities from State F

APPENDIX (J)

Forecasting Project Performance using Dynamic Markov Chains

Client Satisfaction Forecasting Update-Scenario 1

MODEL UPDATE AS AT T-15

	at t = 0.05 T					at t = 0.10 T					at t = 0.15 T					at t = 0.20 T					at t = 0.25 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A						0.6000	0.2000	0.2000	-	-	0.6150	0.1950	0.1900	-	-	0.6255	0.1915	0.1830	-	-	0.6375	0.1875	0.1750	-	-
B						0.1500	0.5000	0.3000	0.0500	-	0.1440	0.5200	0.2885	0.0475	-	0.1398	0.5340	0.2805	0.0458	-	0.1350	0.5500	0.2713	0.0438	-
C						0.0900	0.1800	0.5000	0.1500	0.0800	0.0865	0.1735	0.5200	0.1440	0.0760	0.0841	0.1690	0.5340	0.1398	0.0732	0.0813	0.1638	0.5500	0.1350	0.0700
D						0.0300	0.0500	0.1200	0.7000	0.1000	0.0285	0.0475	0.1155	0.7100	0.0985	0.0275	0.0458	0.1124	0.7170	0.0975	0.0263	0.0438	0.1088	0.7250	0.0963
F						-	0.0200	0.0300	0.2000	0.7500	-	0.0190	0.0290	0.1945	0.7575	-	0.0183	0.0283	0.1907	0.7628	-	0.0175	0.0275	0.1863	0.7688
	at t = 0.30 T					at t = 0.35 T					at t = 0.40 T					at t = 0.45 T					at t = 0.50 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.6510	0.1830	0.1660	-	-	0.6673	0.1776	0.1551	-	-	0.6883	0.1706	0.1411	-	-	0.7108	0.1631	0.1261	-	-	0.7348	0.1551	0.1101	-	-
B	0.1296	0.5680	0.2609	0.0415	-	0.1231	0.5897	0.2484	0.0388	-	0.1147	0.6177	0.2323	0.0353	-	0.1057	0.6477	0.2151	0.0315	-	0.0961	0.6797	0.1967	0.0275	-
C	0.0781	0.1579	0.5680	0.1296	0.0664	0.0743	0.1508	0.5897	0.1231	0.0621	0.0694	0.1417	0.6177	0.1147	0.0565	0.0641	0.1320	0.6477	0.1057	0.0505	0.0585	0.1216	0.6797	0.0961	0.0441
D	0.0249	0.0415	0.1047	0.7340	0.0949	0.0233	0.0388	0.0998	0.7449	0.0933	0.0212	0.0353	0.0935	0.7589	0.0912	0.0189	0.0315	0.0868	0.7739	0.0889	0.0165	0.0275	0.0796	0.7899	0.0865
F	-	0.0166	0.0266	0.1813	0.7755	-	0.0155	0.0255	0.1753	0.7836	-	0.0141	0.0241	0.1676	0.7941	-	0.0126	0.0226	0.1594	0.8054	-	0.0110	0.0210	0.1506	0.8174
	at t = 0.55 T					at t = 0.60 T					at t = 0.65 T					at t = 0.70 T					at t = 0.75 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.7588	0.1471	0.0941	-	-	0.7828	0.1391	0.0781	-	-	0.8055	0.1315	0.0630	-	-	0.8280	0.1240	0.0480	-	-	0.8490	0.1170	0.0340	-	-
B	0.0865	0.7117	0.1783	0.0235	-	0.0769	0.7437	0.1599	0.0195	-	0.0678	0.7740	0.1425	0.0158	-	0.0588	0.8040	0.1252	0.0120	-	0.0504	0.8320	0.1091	0.0085	-
C	0.0529	0.1112	0.7117	0.0865	0.0377	0.0473	0.1008	0.7437	0.0769	0.0313	0.0421	0.0910	0.7740	0.0678	0.0252	0.0368	0.0812	0.8040	0.0588	0.0192	0.0319	0.0721	0.8320	0.0504	0.0136
D	0.0141	0.0235	0.0724	0.8059	0.0841	0.0117	0.0195	0.0652	0.8219	0.0817	0.0095	0.0158	0.0584	0.8370	0.0795	0.0072	0.0120	0.0516	0.8520	0.0772	0.0051	0.0085	0.0453	0.8660	0.0751
F	-	0.0094	0.0194	0.1418	0.8294	-	0.0078	0.0178	0.1330	0.8414	-	0.0063	0.0163	0.1247	0.8528	-	0.0048	0.0148	0.1164	0.8640	-	0.0034	0.0134	0.1087	0.8745
	at t = 0.80 T					at t = 0.85 T					at t = 0.90 T					at t = 0.95 T					at t = 1.00 T				
	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F	A	B	C	D	F
A	0.8685	0.1105	0.0210	-	-	0.8805	0.1065	0.0130	-	-	0.8880	0.1040	0.0080	-	-	0.8955	0.1015	0.0030	-	-	0.9000	0.1000	-	-	-
B	0.0426	0.8580	0.0942	0.0053	-	0.0378	0.8740	0.0850	0.0033	-	0.0348	0.8840	0.0792	0.0020	-	0.0318	0.8940	0.0735	0.0007	-	0.0300	0.9000	0.0700	-	-
C	0.0274	0.0637	0.8580	0.0426	0.0084	0.0246	0.0585	0.8740	0.0378	0.0052	0.0228	0.0552	0.8840	0.0348	0.0032	0.0211	0.0520	0.8940	0.0318	0.0012	0.0200	0.0500	0.9000	0.0300	-
D	0.0032	0.0053	0.0395	0.8790	0.0732	0.0020	0.0033	0.0359	0.8870	0.0720	0.0012	0.0020	0.0336	0.8920	0.0712	0.0004	0.0007	0.0314	0.8970	0.0705	-	-	0.0300	0.9000	0.0700
F	-	0.0021	0.0121	0.1016	0.8843	-	0.0013	0.0113	0.0972	0.8903	-	0.0008	0.0108	0.0944	0.8940	-	0.0003	0.0103	0.0917	0.8978	-	-	0.0100	0.0900	0.9000

	Reporting Period		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	lient Satis Index	Expected Value	The expected client satisfaction performance at the end of the project given the latest actual status is equal to :
			at t = 0.05 T	at t = 0.10 T	at t = 0.15 T	at t = 0.20 T	at t = 0.25 T	at t = 0.30 T	at t = 0.35 T	at t = 0.40 T	at t = 0.45 T	at t = 0.50 T	at t = 0.55 T	at t = 0.60 T	at t = 0.65 T	at t = 0.70 T	at t = 0.75 T	at t = 0.80 T	at t = 0.85 T	at t = 0.90 T	at t = 0.95 T	at t = 1.00 T			
	CONDITION		State Proba	State Proba	State Proba	State Prob	State Probabi	State Probal	State Proba	State Proba	State Proba	State Prob	State Prob	State Prob	State Prob	State Prob	State Proba	State Pro	State Pro	State Pro	State Pro	State Proba	CSI	CSI	
	A		10%	15.54%	17.17%	17.38%	17.08%	16.63%	0.00%	6.94%	10.61%	12.53%	13.51%	14.00%	14.21%	14.26%	0.00%	0.32%	0.57%	0.79%	0.97%	1.14%	1.20	0.01	
	B		30%	27.09%	24.57%	22.85%	21.71%	20.94%	0.00%	14.17%	18.90%	20.53%	21.12%	21.39%	21.58%	21.79%	0.00%	0.53%	1.02%	1.50%	1.94%	2.36%	1.10	0.03	
Initial Probability Vector obtained from company historic records	C		55%	38.92%	32.60%	29.58%	27.92%	26.89%	100.00%	61.77%	45.06%	37.03%	32.80%	30.39%	28.92%	27.97%	0.00%	3.95%	6.73%	8.82%	10.43%	11.71%	1.00	0.12	
	D		3%	12.25%	16.79%	19.41%	21.08%	22.20%	0.00%	11.47%	16.75%	19.39%	20.80%	21.59%	22.05%	22.28%	100.00%	87.90%	78.83%	71.77%	66.22%	61.76%	0.90	0.56	89.68%
	F		2%	6.20%	8.86%	10.78%	12.23%	13.34%	0.00%	5.65%	8.68%	10.53%	11.76%	12.62%	13.24%	13.70%	0.00%	7.32%	12.86%	17.13%	20.44%	23.03%	0.80	0.18	or Below TARGET
	sum		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	Total	0.897	
			1.04	1.03	1.02	1.02	1.01	1.01	1.00	1.01	1.01	1.01	1.00	1.00	1.00	1.00	0.90	0.90	0.90	0.90	0.90	0.90			

Client Satisfaction Performance Behaviour as a Function of Time